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Special feature: Autonomous Ships

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To what extent can technology contribute to improving navigational safety and reducing the workload on seamen, which are important goals for shipping companies? A consortium represented by Mitsu O.S.K Lines is taking up the challenge of conducting demonstration experiment in quay-to-quay autonomous navigation with actual ships in commercial service that had not been attempted by anyone in the past. In writing this paper in the second year from the start of this project, the author reviewed these efforts and summarized the progress to date and the points that we have realized as a shipping company. I have endeavored to describe this work in a way that conveys the actual state of the project, and I hope that this paper will be read by everyone who has an interest in autonomous navigation, beginning with those involved in technology development for automatic navigation and the creation of the necessary framework for autonomous ships.

In the field of ship operation, the technological development for ship operation support and automation and the creation of the necessary legal and regulatory framework in the IMO are underway. Mitsubishi Shipbuilding Co., Ltd. is participating in the Joint Technological Development Program for Demonstration Experiments of Unmanned Ships with the Nippon Foundation. In this demonstration experiment, advanced technologies including AI, image processing and use of cloud technology will be installed on a large ferry, and automated operation technologies will be developed and verified aiming at unmanned ship operation. This paper presents an overview of the technologies installed on the ferry.

In recent years, active technological development has been carried out aiming at autonomous ship operation, and further into the future, unmanned ship operation. This paper presents the definitions of the requirements for development of the maneuvering system and conceptual design for autonomous operation of ships, followed by the composition and technical explanation of the maneuvering control system that controls the movement of the ship, and in particular, approach maneuvering control. Finally, a preliminary report on a demonstration experiment involving ship approach and berthing maneuvering control is presented for an actual large-scale ferry at an actual quay, in which an in-port maneuvering control system incorporating the explained approach maneuvering control and berthing control functions was used.

Some concrete development projects for autonomous ships have been launched all over the world. This paper mainly describes how to evaluate the safety of technologies related to autonomous ships from the standpoint of a classification society together with initiatives of research institute of ClassNK.

Technical Topics

In this research, simplified formulae for the Froude-Krylov force of 6 degrees of freedom (DOFs) were developed with the aim of developing simplified formulae for wave loads using the main hull-form parameters (L, B, d, C_w, C_b, C_m, KG, LCF), which can be used with any arbitrary ship type and size. The developed formulae for the Froude-Krylov force are expressed by explicitly using hull-form parameters, together with the wave direction and wave length. Numerical analyses using the actual hull-forms of 154 merchant ships of various types and sizes were compared, the results confirmed that the formulae possess satisfactory accuracy under all conditions.

Ship designers needs to be able to reasonably estimate hull motion in waves from various aspects such as passenger safety, ride comfort and wave loads for ship designs. Nowadays, hull motion in waves is accurately estimated by seakeeping analysis tools such as the 3-D panel method and the estimation is practically used for all hull design and standard development. At the same time, however, there also is high demand for methods which allow for more simple estimations of hull motion to be made that do not rely on numerical analysis.

This paper introduces the development of a general-purpose and high precision closed formula for maximum loads with an exceedance probability of 10^{-8} by formulating the long-term prediction for ships of any size or type.

Moves toward decarbonization are accelerating at the governmental level. However, climate changes initiatives, that is, efforts to promote voluntary decarbonization at the private-sector level originating from the financial sector, represented by institutional investors and banks, have now become a global trend, and cannot be ignored, when Japanese companies are to continue their activities in international supply chains. This paper presents an overview of these international climate change initiatives, and describes ClassNK's support business for Japanese companies responding to those initiatives.

With the maritime industry now engaged in efforts to realize digital transformation (DX), ClassNK announced the "ClassNK Digital Grand Design 2030," which summarizes the expected roles of ship classification societies in digital society by around the year 2030, and launched "Innovation Endorsement" as a framework for certifying innovative technologies and efforts. This paper provides an outline of the Digital Grand Design, and introduces Innovation Endorsement and its related services as part of efforts toward its realization.

Recent Trends and Issues for Practical Application of MASS

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1. INTRODUCTION

As many of the readers of this paper already know, active research and development, including demonstration experiments, with the aim of practical application of the ships called maritime autonomous surface ships (MASS), unmanned ships and autonomous ships are underway in countries around the world. The author will offer his own definitions of the differences among MASS, unmanned ships and autonomous ships in the following. However, in this paper, these various types of ships will be referred to collectively as MASS.

In spite of some differences in the level of interest in each country, the purposes of research and development of MASS can be classified as “improved safety of ship operation,” “reduction of workload on seafarers,” “response to shortages of seafarers,” “reduction of environmental impacts,” “reduction of ship operation costs,” and “technical interest.” Although it is currently difficult to conduct field surveys in other countries because of restrictions on overseas travel due to the COVID-19 pandemic, there is a real feeling that the problems faced by other countries are the same as those in Japan in many cases. Put another way, if technologies that solve the problems confronting Japan are developed, there will be many opportunities to market those technologies to other countries.

On the other hand, various other countries are not simply promoting technology development, but are also proactively engaged in activities for developing standards and rule-making from the stage of technology development. Likewise, in Japan, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) established “Safety Design Guidelines of Maritime Autonomous Surface Ships” [1] in December 2020, and the Japan Ship Technology Research Association conducted a “Safety Evaluation of MEGURI 2040 (Unmanned Ship) Project” with the support of the Nippon Foundation. As part of that work, activities aimed at international standardization were also begun, including “summarizing the safety requirements considered necessary for realizing unmanned ships, and development of a draft of guidelines unifying the levels of automated and remote operation, and automation” [2]. Needless to say, since many members of ClassNK are participating in these projects, Japan has created a system for communicating not only information related to technology development, but also the development of legal systems to other countries.

In view of this social situation, this paper will introduce major trends in research and development on MASS technologies in Japan and other countries, and will describe what the author considers to be the technological issues and necessary research and development items.

2. WHAT AREMASS?

2.1 Definitions of Maritime Autonomous Surface Ships (MASS) and Other Terms

First, the author’s definitions of maritime autonomous surface ships (MASS), unmanned ships, autonomous ships, an automated navigation ship, an unmanned navigation ship and an autonomous navigation ship will be presented. The reader should understand that these are not generally recognized definitions, but are simply defined by the author using these various terms to enable easier understanding of the trends in technology described in this paper. The reader should also note that the official definition of MASS and the meaning used in this paper may differ, as definition of MASS is still under study in ISO/AWI 23860 in the International Organization for Standardization (ISO) [3].

2.1.1 Automated Navigation Ship, Autonomous Navigation Ship and Unmanned Navigation Ship

“An automated navigation ship” means the entirety of a ship which utilizes some type of automatic control function and is capable of sailing without direct human operation of devices related to navigation, such as the rudder and propellers. Heading

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control and course tracking, which are already installed in many existing ships, are examples of automatic control functions, and a ship that navigates by using these functions is also an automated navigation ship. As described below, an autonomous navigation ship and an unmanned navigation ship also use automatic control functions, and thus are types of an automated navigation ship.

"An autonomous navigation ship" refers to the automated navigation ship in which the actions of recognizing objects in the waters around a ship using various types of sensors, judging whether those objects pose a danger of collision or not, taking action to avoid the objects if a danger of collision exists, and then returning to an appropriate course toward the set destination after completing the evasive action can be performed automatically without the intervention of human judgment. Although the heading control and course tracking control do not have the cognitive judgment function of recognizing and avoiding obstacles, an automatic control system that includes this cognitive judgment function is an important feature of ships and has become a target of technology development. However, this definition only refers ships which possess functions that are capable of performing judgments and operation related to steering without human intervention, and is not related to whether seafarers who can perform manoeuvring operations actually go aboard the ship or not.

"An unmanned navigation ship" is a ship which does not carry a crew, and thus is a type of the automated navigation ship. This type of ship is either equipped with the functions of the above-mentioned autonomous navigation ship, or navigates based on manoeuvring commands transmitted from a human controller at a remote location to the ship by some means of communication. Although the definition of this type means the ship cannot carry seafarers, it can carry passengers. Considering the possibility that communications with the remote control center may be interrupted, it is hoped that this type will be equipped with the functions of the autonomous navigation ship. However, a ship which is not equipped with autonomous navigation functions, but is controlled remotely by transmission of navigation commands related to operation of the rudder, propellers, etc. can also be classified as an unmanned navigation ship, provided it does not carry seafarers who can perform manoeuvring operations.

2.1.2 Automated Ships, Autonomous Ships and Unmanned Ships

The common feature of the three types of ships in the previous section is some form of automation (or remote control) of the navigation function. However, ship operation is not limited to the navigation function defined as "sailing on a set course at a certain speed while avoiding obstacles." Ship operation also includes various other types of work such as "deberthing (leaving the pier/quay)," "accelerating/decelerating," "transitioning from a sailing condition to an anchored condition by dropping anchor offshore," "transitioning from an anchored condition to a sailing condition by weighing anchor offshore," "berthing (mooring at a pier/quay)" and taking on passengers or cargo, and unloading. Moreover, the work of shipping companies does not end with the work on shipboard, but includes cooperation with land-based equipment and also requires coordination with the operations of multiple other ships, and not simply the operation of one ship. Considering the fact that ship operation is realized by the totality of all these tasks, in this paper, the system that performs all of these tasks is called "operation." In this paper, if automated navigation ships use automation technology to perform this type of ship operation, the operated ships are called "automated ships." Similarly, autonomous navigation ships which perform ship operation are called "autonomous ships," and unmanned navigation ships are called "unmanned ships." Because autonomous navigation ships and unmanned navigation ships are types of automated navigation ships, autonomous ships and unmanned ships are also categorized as automated ships.

2.1.3 Marine Autonomous Surface Ships (MASS)

The term maritime autonomous surface ships (MASS) has not yet been defined in Japan, and also remains to be defined in other countries. At international conferences on MASS, the participating marine equipment companies, communication technology companies and startups have made presentations focusing on application of technologies developed by the respective companies themselves, but in any case, a ship equipped with autonomous functions is assumed, as can be understood from the word "autonomous." Therefore, in terms of the definitions in section 2.1.2, "autonomous ships" is the closest approximation to MASS. At present, however, autonomous functions are still in the development process, and experiments are largely limited to automatic control devices for which only some autonomous functions have been developed. Thus, under the present conditions, it would be more appropriate to call MASS "automated ships." In this paper, MASS are referred to simply as "automated ships."

2.2 Hardware Configuration of MASS

The hardware configuration of MASS which is the target of research and development is shown in the illustration in Fig. 1.

Basically, the hardware consists of multiple autonomous ships, a remote control room (Control Center), which remotely monitors multiple autonomous ships from a remote location and issues instructions corresponding to their conditions, and a communication system for exchanging information between autonomous ships and the Control Center. Because monitoring and observation equipment for observing the condition of the waters where the autonomous ships are navigating and weather and maritime meteorology conditions are installed in ports, on buoys and so on and are also useful for information sharing, a system configuration which can be linked with this monitoring and observation equipment is desirable.

For safe use of MASS, implementation of functions for recognition and judgment of conditions and navigation are required in the ships themselves. Therefore, a ship which is to be used as MASS must be an autonomous navigation ship.

Regarding the Control Center, general control centers which perform operation control are also used by railways, in which automated operation technology was applied earlier in the sense that an operator is not onboard the train. It is necessary to create an analogous system for ships to enable monitoring of ships at sea from land and transmission of commands from a remote location whenever necessary.

It is also necessary to construct a cable and wireless communication environment for use in exchanges of information between the autonomous ships and the Control Center and remote observation devices.

2.3 Purposes of Development of MASS

Although there are some differences depending on the country, the purposes of research and development for MASS are as follows.

2.3.1 Improved Safety of Ship Operation

To mention a development in the automotive field, collision damage reduction braking control devices (automatic brakes) will be legally required on new automobiles in Japan beginning in November 2021 [4], as the incidence of accidents can be reduced by installing this type of automatic control device. Since there is concern that humans may overlook dangerous conditions due to fatigue and other factors, resulting in poor judgment, the development of automatic control devices that assist human judgment is required in order to reduce these kinds of accidents.

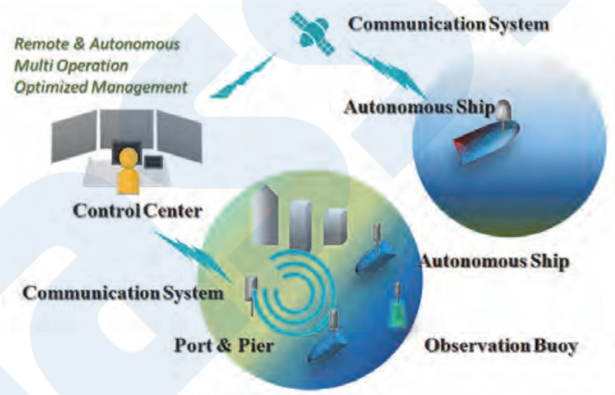

Figure 1 Hardware configuration of autonomous ships

2.3.2 Reduction of Workload on Seafarers

In the current environment, the use of the heading control function reduces the workload of manual rudder operation to maintain the target course, allowing seafarers to put greater effort into watching the surrounding area. If autonomous ships can be realized, a further reduction of the burden of watchkeeping work will also be possible.

2.3.3 Response to Shortage of Seafarers

The work of seafarers is sometimes seen as a 3K (hard, dirty, dangerous) job in Japan and as a 3D (dull, dirty, dangerous) job in other countries, and as a result, the number of young jobseekers in this field has declined. Particularly in coastal navigation, since the percentage of seafarers aged 50 years or older is approximately 46 % [5], it is easy to imagine that labor shortages become even more serious in the near future.

2.3.4 Reduction of Environmental Impacts

Although autonomous ships do not contribute directly to reducing environmental impacts, if unmanned navigation ships can be realized, the problem of long working hours of seafarers will not arise. As a result, it will be possible to reduce the sailing speed of ships, which will reduce fuel consumption and thereby contribute to reducing the load on the environment.

2.3.5 Reduction of Operating Costs

If unmanned ships can be realized, it will be possible to reduce the cost of hiring seafarers and the cost of meals and other incidental costs during voyages. It will also be possible to increase the volume of cargos by eliminating crew living space in ships.

2.3.6 Technical Interest

Because research and development on self-driving technologies is progressing, particularly in the automotive field, research is also being promoted from the viewpoint of the pure technical interest of engineers, focusing on the question of whether self-driving technologies can also be used in ships.

3. EXAMPLES OF TECHNOLOGIES RELATED TO MASS IN JAPAN AND OTHER COUNTRIES

3.1 Overview of Trends in Related Technology Development in Japan and Other Countries

It goes without saying that a large investment of several $100 million will be necessary in order to develop MASS. Although presentations on technologies which are still under development is unavoidable for raising funds from investors, there are many projects in which a grand presentation of the concept using a computer-graphic promotional video is made before the ship is actually constructed and demonstration experiments are carried out, or even assuming ship construction has been completed, before any significant progress has been achieved in developing the software needed for automatic operation. Although this paper includes some slightly older ships, here, we will introduce representative examples of demonstration experiments, with the focus narrowed to automated operation ships using comparatively large-scale ships in actual service, with the aim of developing MASS.

3.2 Examples of Related Technologies in Other Countries

3.2.1 Rolls-Royce

In December 2018, Rolls-Royce and Finferries carried out a demonstration of a ship classified as an autonomous operation ship, as defined previously, in which fully autonomous navigation was achieved between Parainen and Nauvo by the car ferry *Falco* (length overall, LOA: 53.8 m). Figure 2 shows automatic berthing by the *Falco*. The ship was equipped with an obstacle detection system which integrated sensors and AI and avoided obstacles based on information from this obstacle detection system, and also performed automatic berthing under fully autonomous navigation control with absolutely no operation by seafarers [6]. Sea trials with a total time of about 400 hours were conducted as part of system development. It may be noted that Kongsberg acquired the merchant ship division of Rolls-Royce Commercial Marine (RRCM), which had carried out this SVAN Project (SVAN: Safer Vessel with Autonomous Navigation), from Rolls-Royce by Kongsberg in April 2019 [7], and there have been no notable press releases concerning the SVAN Project since that time, presumably because the members of the Rolls-Royce team responsible for research and development of the autonomous ship established Groke Technologies [8].

Figure 2 Scene of automatic berthing of *Falco* [6]

3.2.2 Kongsberg Maritime

In a joint project with Bastø Fosen, Kongsberg and the Norwegian Maritime Authority (NMA), in February of 2020, Kongsberg Maritime installed an automatic operation system on the car ferry *Bastø Fosen VI* (LOA: approx. 140 m), which is operated by Bastø Fosen, and successfully conducted an experiment with MASS as defined in this paper, demonstrating autonomous operation from leaving port to entering port under the conditions of normal service between Horten and Moss [9]. Figure 3 shows the scene on the ship's bridge published in a press release.

3.2.3 Wärtsilä

In January of 2021, Wärtsilä announced that it had installed its automated navigation system, Wärtsilä SmartMove Suite, on a 42 year old ship, the *American Courage* (LOA: 190 m), and performed navigation including automatic berthing and unberthing on a waterway called the "Crooked River" in Cleveland, Ohio (US). Figure 4 shows the scene of navigation by the *American Courage*. This vessel is also classified as MASS, as defined in the previous chapter. Here, it is noteworthy that automated navigation was realized in both going ahead and astern operation, as there is no space to turn round the vessel in this narrow waterway [10].

Figure 3 Scene during voyage of *Bastø Fosen VI* [9]

Figure 4 Scene during voyage of *American Courage* [10]

Figure 5 MASS of U.S. Department of Defense [11]

Figure 6 Combined dredger-and-oil recovery ship, *Kaisho Maru*

3.2.4 U.S. Department of Defense

Also in January 2021, the U.S. Department of Defense announced that MASS, as shown in Fig. 5, had successfully navigated a route of more than 4,700 miles from the Gulf Coast to the coast of California via the Panama Canal. Approximately 97 % of the voyage was performed under autonomous navigation, and one of the few situations when the vessel was operated by the small crew onboard was during traversing the Panama Canal[11]. Although the press release from the U.S. Department of Defense used the word "unmanned," under the definitions used in this paper, this vessel is classified as an autonomous navigation ship/MASS because the experiment was conducted with a crew onboard.

3.3 Examples of Development of Related Technologies in Japan

3.3.1 Japan Marine United

The combined dredger-and-oil recovery ship shown in Fig. 6, the *Kaisho Maru* (LOA: 103 m), was developed by the present Japan Marine United Corporation and is operated by the Kanmon Waterway Office of the Kyushu Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism (MLIT). This vessel features an "automatic mooring and automatic land discharge system," in which berthing, discharge of dredged sand on land and unberthing are automated, and has performed automatic operation since April 2004 [12]. The automatic mooring and automatic land discharge system was realized by a set of functions comprising course tracking control, which follows a predetermined port entry and berthing course, and an automatic mooring system using equipment installed on the quay side [13] [14]. Since this ship utilizes an automatic control system under an environment in which crew members perform watch duty and is not equipped with an obstacle detection and avoidance function, the ship type is classified as an automated navigation ship and not as an autonomous navigation ship. However, in the sense that the berthing and unberthing operations have been automated, it can be called an automated operation ship.

3.3.2 NYK Line

Nippon Yusen Kaisha (NYK Line) installed an optimal route program on a large-scale pure car carrier, the *Iris Leader* (LOA: approx. 200 m), as shown in Fig. 7, and made a day-and-night voyage intermittently under the control of that program, while maintaining the normal crew watch system, over a test route from Xinsha, China to the Port of Nagoya in Japan, and then from the Port of Nagoya to the Port of Yokohama (the test area included Japan's coastal waters but excluded bays) [15]. Since the program also performs collision avoidance, this can be considered an experiment with an autonomous navigation ship, as defined in this paper.

3.3.3 Mitsui E&S Shipbuilding and 4 Other Companies

In May 2021, Mitsui E&S Shipbuilding Co., Ltd., Mitsui O.S.K. Lines, Ltd., Tokyo University of Marine Science and Technology, Akishima Laboratories (Mitsui Zosen) Inc. and MOL Ferry Co., Ltd. carried out a demonstration test of automatic pier docking and undocking at an actual quay in the Port of Oarai, Ibaraki Prefecture, Japan, using a large-scale car ferry owned by MOL Ferry, the *Sun Flower Shiretoko* (LOA: 190 m), successfully demonstrating automatic pier docking and undocking at an actual quay by a large-scale car ferry for the first time in the world [16]. Figure 8 shows scenes from the automatic pier docking and undocking simulation and the demonstration experiment. Since the press release did not mention collision avoidance, whether the ship is equipped with autonomous functions is unknown. Therefore, under the definitions in this paper, this can be considered to be an experiment with an automated navigation ship.

Figure 7　Large-scale pure car carrier, *Iris Leader* [15]

Figure 8　Scenes from automatic pier docking and undocking simulation and demonstration experiment with large-scale car ferry, *Sun Flower Shiretoko* [16]

4. ISSUES FOR REALIZING MASS

4.1 Overview of Issues for Realizing MASS

The term “ship” covers a wide range of vessels from mini-boats with a length of several meters to large ships with LOAs of several 100 meters. Moreover, differences are not limited to size; numerous kinds of ships with different shapes also exist, including pleasure boats, fishing boats, cargo ships, tankers and car carriers, among others. Therefore, the location and height of the pilothouse, the number and response of the propellers, and the types of devices installed to acquire information concerning the surrounding environment will also differ completely depending on the ship. Furthermore, even on one voyage, the length of the voyage will differ depending on the course, and the work required during the voyage will also differ greatly. On the other hand, because the universities, research institutes and companies which are engaged in research and development aiming at realization of MASS is extremely limited, even from the global viewpoint, and these organizations are promoting research and development targeting ships in which each has a deep interest, it cannot be said that research and development is being carried out with skillful coordination in the ship industry as a whole.

Therefore, in this paper, the issues which require study are arranged in terms of the functions required in MASS, the waters where those ships are used and the ship size, within the range of the author’s knowledge.

4.2 Functions Required in MASS

As mentioned in section 2.1.2, it is necessary to realize the functions of “sailing on a set course at a certain speed while avoiding obstacles.” “undocking,” “accelerating and decelerating,” “transitioning from a sailing condition to an anchored condition by dropping anchor offshore,” “transitioning from an anchored condition to a sailing condition by weighing anchor offshore” and “docking.”

The function of docking and undocking from a quay (or pier) has been realized by linkage between a car ferry and equipment on the land side, as noted in Chapter 3. On the other hand, the author was unable to find examples of research and development related to anchoring, although this may simply reflect the limits of literature research.

As technologies for avoiding obstacles while sailing, the first requirement is a function for detecting obstacles. This detection function is not limited only to detecting other ships, but also includes incapacitated vessels (vessels not under command), vessels restricted in the ability to maneuver, etc. and fishing nets and buoys, floating objects and channel buoys. A judgment capacity is also required; that is, it is necessary to judge differences in the priority order depending on the encounter situation and the condition of navigation, and determine how to avoid a collision accordingly. In the case of obstacle detection, development of systems utilizing artificial intelligence (AI) is being carried out in many countries. In Japan as well, the Japan Ship Technology Research Association launched a “Research Committee on Image Recognition Systems for Marine Use” in June 2019. This organization is collecting and organizing big data in image form for use in the development of AI for obstacle recognition at sea. The planned period of activities by this Committee is 3 years, ending in FY 2021. The Committee was set up based on the thinking that development of the image big data on marine areas and teaching data should be carried out jointly with industry, and development of the AI technology and applications should be done by systems companies or others as a “competitive area.” The work of the Committee is being carried out in two stages, Phase I and Phase II. In Phase I, the decision of the specifications of the image data and trial production of the teaching data were carried out in FY 2019. From FY 2020, this work moved to Phase II, and collection of image data, production of teaching data and image big data, including the teaching data, is now being planned to be conducted over a 2-year period [17].

4.3 Differences Depending on Waters [18]

In closed waters like those in a park or a theme park, the condition of a ship sailing in those waters and its course can be understood almost completely. In this case, even if someone unexpectedly falls overboard, the accident can be discovered easily, not only by watching by cameras installed on the ship, but also by monitoring the entire route with surveillance cameras installed separately around the body of water. At present, it is considered necessary to leave judgments of obstacles that should be avoided and obstacles that need not be avoided such as waterbirds and the like to human observers, but in the future, automatic detection by AI is expected to become possible. When an obstacle is discovered, stopping the ship before it collides with the obstacle can be considered the minimum obstacle avoidance function. Moreover, because the cruising distance is short in closed bodies of water, the necessary operating time of the propulsion system is also considered to be short. If the operating time is short, maintenance can be carried out by providing opportunities separately, and automation is easy because the control necessary for sailing is normally simple. In automated pier docking and undocking, manoeuvring control can be simplified by providing suitable piers for the automated ships.

When operating on a course with good visibility and a very short distance of a few 100 meters, for example, when crossing a river or a canal, it is comparatively easy to monitor the entire route by installing surveillance cameras, as is done in the above-mentioned closed waters, and the functions required in the propulsion system are also similar to those used in closed waters. As a difference from closed waters, it is not necessary to assume that other vessels may enter the own ship's course in closed waters, but this possibility cannot be ignored if the waters are not closed. A higher-level obstacle detection function and obstacle avoidance function are required so as to discover other vessels that may intrude into the own ship's course, determine their direction and navigate so as to avoid a collision. Moreover, depending on the environment, it may also be necessary to consider the effects of tides and currents, and in this case, a more advanced autonomous navigation function is necessary.

When navigating a route which is predetermined but lacks direct visibility, for example, when sailing the length of a river or canal, in addition to the conditions of the above-mentioned very short routes, the number of obstacles that should be detected will also increase. Although the ship may stop at multiple points, the voyage time is long; therefore, a more reliable propulsion system is required.

In the case of courses such as navigation in a port, a large number of ships of different sizes are present in comparison with navigation on a river, the directions of those other ships are more varied, and detection of fishing nets and other fishing gear is also required. Improvement of the obstacle detection function is necessary under these conditions. Because the body of water is larger and the size of the waves also increases, a grasp of weather conditions and shiphandling responding to those conditions is required. Tugboats and pilot boats also present problems: Although automatic operation is conceivable, it is necessary to consider not only the simple manoeuvring of these vessels, but also the movements of the ships which they are assisting. In this case, even more advanced steering control is demanded.

In the shiphandling aspect, in cases where a ship leaves a certain port and then enters another port after a voyage of several hours to several days, if the shiphandling system is on a level that enables autonomous navigation in the port, it is considered possible to use the same system. On the other hand, improved reliability is necessary in the propulsion system so that the system can be used for several days in a completely unmanned condition, and ultimately, a maintenance-free propulsion system is needed.

Although ocean-going voyages may last from several days to several weeks, various types of ship maintenance work are required on these voyages in addition to simple operation to transport the cargo. Performing maintenance work during voyages contributes to reducing work when the ship is in dock, resulting in a longer available ship operation time. Since automation of maintenance work is extremely difficult, it is thought that maintenance will continue to rely on human labor, even assuming automated shiphandling is possible.

4.4 Differences Depending on Ship Size [18)]

Because Japan's Ship Safety Act does not require surveys of small-sized vessels with a length of less than 3 meters and output of less than 1.5 kW, and the Act on Ships' Officers and Boats' Operators does not require that an operator possessing a small craft operator's license be on board and operate the boat, experiments can be performed easily with these craft. However, from the viewpoint of the Act on Preventing Collision at Sea, care is advised, as the above-mentioned provisions do not necessarily mean that experiments are permitted. Due to the small output of craft with outputs of less than 1.5 kW, the size of the vessels and the waters where they can be used are limited, and there are also limitations on the steering performance of these craft. Thus, care is necessary when evaluating the results of experiments and the possibility of development of the experimental results to other locations.

Small-sized vessels with gross tonnages of less than 20 tons have good maneuverability and a small turning circle, but are greatly affected by waves and other conditions. When a small ship is operated manually, fine steering control from a micro viewpoint is performed, even though the ship is sailing in a straight line from the macro perspective. For example, if the wave caused by another ship is sighted, the ship operator adjusts the heading toward the wave to minimize shaking of the own ship. This means it is necessary to realize a function that not only follows the set course, but can also make this kind of fine steering adjustments. Moreover, even assuming it is possible to measure the ship's heading as it changes instantaneously under the effect of external disturbances, the ship will return to the original heading when the external disturbance ceases; thus, it is necessary to consider the maneuverability of the ship when using the measured values.

Although ships with gross tonnages exceeding 20 tons range from small vessels with LOAs of around 20 meters to very large ships with LOAs of several 100 meters, there are no names that provide a detailed classification of these ships based on size. Maneuverability also differs greatly depending on the conditions, as the draft of tankers and cargo ships may change by more than 10 meters when empty and fully loaded, and car carriers are extremely susceptible to the effects of wind due to their very large above-water structure. Therefore, it is necessary to design a control system which is suitable for the conditions, even in the same ship. Since maneuverability also varies, the distance necessary to avoid a collision after an obstacle is discovered will vary. As a result, the distance at which the sensors must detect obstacles will change and the performance required in the sensors will differ accordingly. Regarding propellers, in the case of small ships, manoeuvring is possible, preconditioned on switching between forward and reverse rotation of the propellers, as switching between forward and reverse rotation is comparatively simple. However, steering by changing the direction of propeller rotation is not realistic in ships with LOAs of several 100 meters.

4.5 Linkage with Land-based Equipment

If all shiphandling work is performed only from the ship side, the problems are inevitably complex. For example, in mooring operation, if it is possible to provide an automatic mooring and automatic land discharge system like that used in operation of the *Kaisho Maru* introduced in section 3.3.1, the work of passing mooring lines between the ship and the land side can be eliminated. If it is possible to use a berthing method like that used in car ferries, which take on and discharge automobiles from the bow and stern, berthing control can be performed more easily in comparison with docking the ship alongside a quay.

Because the equipment in a remote control center unavoidably relies on a wireless communication network to acquire all information on the operating condition of ships and the waters during voyages, the volume of information which can be transmitted and received and the transmission speed are inevitably limited. However, depending on the waters where ships operate, installation of cameras on the land side can enable more effective monitoring of the waters than installation of cameras on every ship, since a cable transmission network can be used effectively, and it may also be possible to acquire bird’s eye information on the entire water area by properly selecting the camera installation points. In particular, using a cable communication network can be expected to have various benefits from the viewpoints of transmission volume, speed and cost.

In short, the problems that must be solved can be simplified by effectively utilizing land-based equipment, rather than attempting to solve all the problems related to ship operation from the ship side alone. Since it may also be possible to reduce costs, it is necessary to understand the status of development of land-based equipment, and to be aware of the advantages of actively utilizing these technologies.

4.6 Creation of Legal System and International Standardization

Recently, the Maritime Safety Committee of the International Maritime Organization (IMO) concluded its 103rd session (MSC 103) and completed a regulatory scoping exercise (RSE) for analysis of the effects of MASS on the existing regulatory system. As a result of this study, which began in 2018, it was concluded that revisions of treaties corresponding to the level of automation and development of commentaries will be necessary for some maritime-related treaties. Among these, however, it was concluded that revisions and commentaries will not be necessary for most treaties in the case of “automated ships equipped with automation system that support the decision making of seafarers” (Degree One automation). Agreement was also reached on the following as priority items for future study [19].

○Planning of work to develop standards related to MASS
○Definition of MASS and review of levels of automation
○Development of the definitions of MASS terminology
○Addressing high priority issues specific to MASS
(Positioning of “master,” “remote-control station/center,” etc. in MASS)
○Development of guidelines for application of automatic navigation systems, etc.

In the future, increasingly active efforts are expected in the development of more concrete rules for social implementation of developed technologies. The Japanese side must also participate actively in these rule-making activities in order to strengthen the international competitiveness of this country’s maritime industries. In addition to the development of rules related to the developed technologies, it will also be necessary to study and create a legal system for the operation management engineers who use the developed technologies, or in more concrete terms, qualification and training for the seafarers who will crew ships using automation technologies and the personnel who will perform operational control from remote control centers.

5. CONCLUSIONS

This paper has described recent trends for practical application of maritime autonomous surface ships (MASS) as identified by the author, and the items which the author considers to be issues in research and development for practical application of MASS. Due to the extremely active publicity of other countries in connection with research and development on MASS, some may feel that the technologies of companies in other countries are more advanced than those in Japan. However, a detailed examination shows that there are no large technical differences in comparison with the technologies now under research and development in this country. On the contrary, because many overseas technologies are being developed focusing on only some problems, there are also some scattered examples of technologies that fail to satisfy the current collision regulations (COLREG convention) and others. Moreover, even assuming that MASS are applied practically, this does not mean that all ships will be MASS. Therefore, coexistence of MASS and conventional ships will still be necessary. In other words, it will be necessary to confirm the contents of various existing treaties and carry out technology development that complies with their requirements. In technologies provided from Japan, it is expected that this country plans disseminate technologies which fully comply with the relevant treaties. Moreover, since various demonstration experiments have been conducted in Japan in recent years, Japan intends to publish the results of those demonstration experiments and proactively issue rules and guidelines necessary for safe operation of MASS based on the results of those experiments so that the technologies developed in Japan will become the standard technologies for MASS .

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Research and Development of Collision Risk Decision Method for Safe Navigation and Its Verification

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1. INTRODUCTION

Innovation of ICT technologies has advanced rapidly in recent years, and research and development of new technologies using big data has been actively pursued in various industries, including the automobile industry. In the marine transportation industry, joint industry governmental-academia research and development of new technologies using big data has also been promoted internationally, especially in Europe, and the impact of that innovation has spread to the marine transportation business.

In Japan as well, industry, government and academia have mobilized their total capabilities to conduct research and development on technologies using ship big data, which will be an important factor in future development, in order to strengthen the international competitiveness of the marine transportation industry in Japan, with a view to finding opportunities for new marine transportation businesses in line with this global trend.

As part of these efforts, Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) positioned the year 2016 as the "first year of the productivity revolution," and the Ministry's Maritime Bureau has been promoting a "Maritime Productivity Revolution" initiative (commonly called "i-Shipping"). In the field of ship operation in i-Shipping, the Bureau provided subsidies for a total of eight technical development projects, including the development of a monitoring technology for the hull structure by FY 2017, with the aim of improving the safety and efficiency of ship operation by supporting research and development of advanced devices and systems utilizing technologies such as IoT (Internet of Things) for ships and marine devices and big data analysis.

This paper report introduces the efforts of Nippon Yusen Kabushiki Kaisha (NYK Line), MTI Co., Ltd., Japan Marine Science Inc., Furuno Electric Co., Ltd., Japan Radio Co., Ltd.,(JRC) and Tokyo Keiki Inc., which are participating in a "study on collision risk judgment and autonomous operation of vessels (Field: Operation support using a rocking and operation simulator)," which is one of the projects selected for the initiative (subsidized research and development projects for advanced safe ship technologies).

The significance of work in this study is to secure safety in navigation against risks associated with the recent trends of larger and faster ships, more congested ship traffic and fewer crew, and to reduce the work burden. To achieve these purposes, three topics were studied: "I. Research and development of a collision risk decision method," "II. Research and development concerning autonomous ship," and "III. Navigation support tool using computer vision." This report introduces the results of "I. Research and development of a collision risk decision method."

2. BACKGROUND OF RESEARCH AND DEVELOPMENT OF COLLISION RISK DECISION METHOD

Post-accident investigations have found that insufficient watch by navigation officers accounts for almost half of ship accidents. Therefore, accurate identification of ships at risk of collision in collision avoidance navigation is considered to be the most important task.

As a risk level index for collision between one's own ship and another ship, it is a common practice to give the master / navigation officer a risk level index using the distance of closest point of approach (DCPA) and the time to closest point of

* Japan Marine Science Inc.
** Furuno Electric Co., Ltd.
*** Japan Radio Co., Ltd.
**** Tokyo Keiki Inc.
***** MTI Co., Ltd.

approach (TCPA) after calculating the closest point approach (CPA) with ARPA installed on the marine radar.

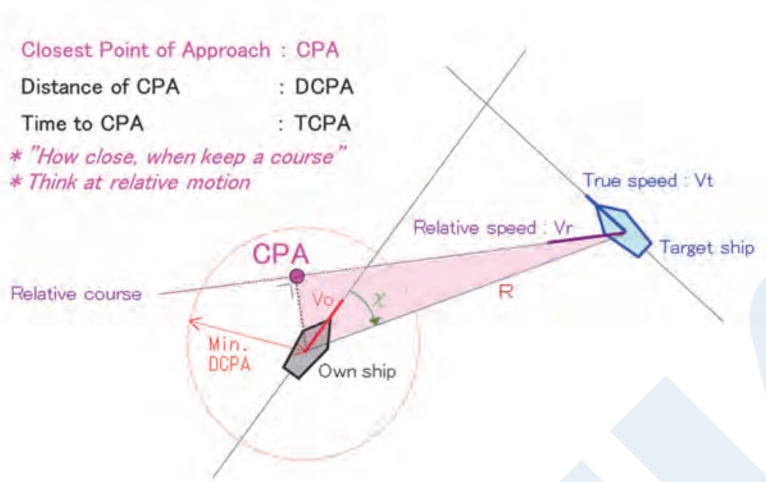


Figure 1　Information based on close point of approach

However, the risk level index using DCPA/TCPA does not consider factors such as encounter situations between the own ship and another ship. In congested waters such as Tokyo Bay and the Singapore Straits, many ships are judged as dangerous based only on DCPA/TCPA settings, and alarms are frequently issued. As a result, the following problems arise.

- Difficult to monitor ships according to collision risk
- Cross-check is difficult between compare visual information and DCPA/CPA information
- Reduced attention of master / navigation officer to alerts

In contrast, some past studies mentioned methods for indicating an area where a ship may collide with another ship (collision risk area), such as PAD (Predicted Area of Danger), DAC (Dangerous Area of Collision) or OZT (Obstacle Zone by Target), which means a zone of obstruction by another ship.

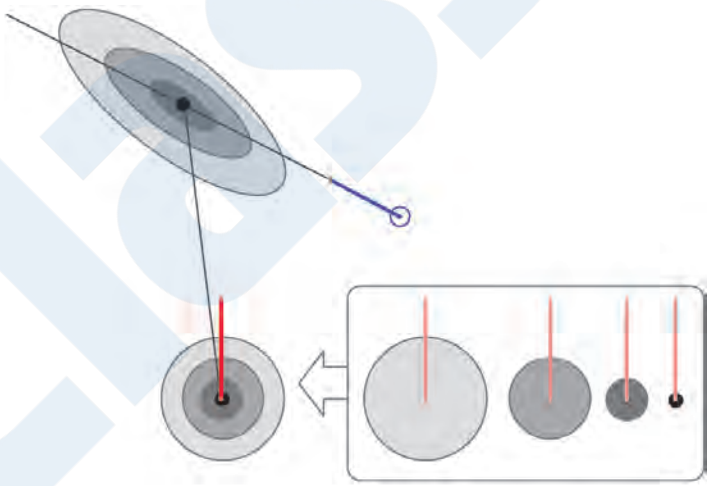


Figure 2　Illustration of collision risk area

Displaying a collision risk area enables the master / navigation officer to determine the risk of collision in the form of a plane rather than a dot, and would be very helpful for formulating a collision avoidance navigation plan by showing the master / navigation officer the area where the ship may collide with another ship. However, as one problem, it is difficult to use this method as a reference for formulating a collision avoidance navigation plan because the ship's course may be filled with collision risk areas in congested waters such as the mouth of Tokyo Bay mouth and the Singapore Straits.

In order to reduce collision accidents in spite of this problem, it is important to identify the characteristics of human cognition of collision risk, appropriately reflect those characteristics in the functions of machines and enable humans to use those functions appropriately. The following figure summarizes the characteristics and comparison of a machine and a human being in terms of collision risk cognition.

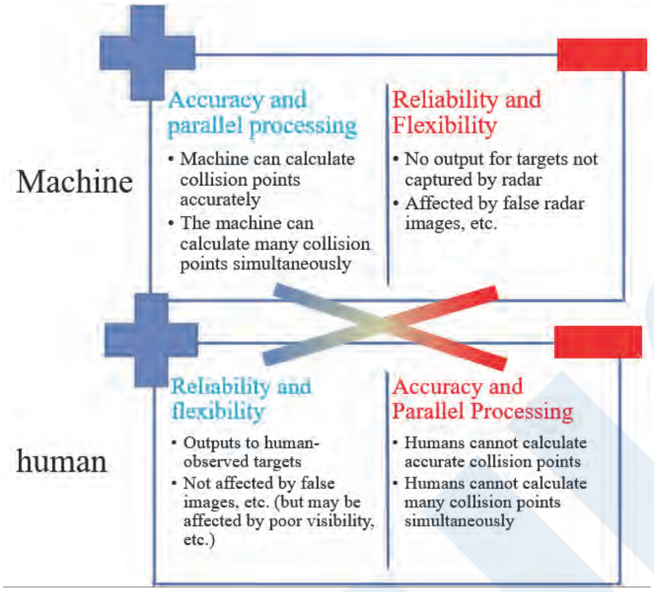


Figure 3 Comparison of collision risk cognition by machine and human

In order to solve the problem described above, this study presents the risk of collision between a ship and another ship in the form of an index in a manner that matches the master / navigation officer's sense of risk, and establishes a means of notifying the master/navigation officer of a possible collision and a collision avoidance policy in a manner that enables the master/navigation officer to make a decision intuitively based on this index. Furthermore, in this study, the method for displaying an area where the ship and another ship may collide was improved to make the area closer to what the master / navigation officer recognizes as a collision risk area, and the problem that congested waters are filled with collision risk areas, as described above, was also improved.

In this study, over five years, more than fifty acting masters and navigation officers from NYK Line and over twenty students from Tokyo University of Marine Science and Technology and Kobe University participated as subjects, and data for developing a collision risk level index were obtained in order to validate the developed devices. The following sections describe the specific contents of the research and development by Furuno Electric, Japan Radio and Tokyo Keiki, which developed collision risk level indicators and devices, and an analysis by Japan Marine Science, which led an experiment to verify the effects of the developed devices.

3. TECHNOLOGICAL DEVELOPMENT

3.1 Technological Development by Furuno Electric Co., Ltd.

In safe operation of a ship, it is important for the master / navigation officer to notice any collision risks present around the ship without fail and make decisions on operation at the correct timing. However, during navigation in actual congested waters, masters / navigation officers must handle and make judgments on so many ships that they may overlook or be late in recognizing collision risks. In addition, in encounter situations involving any of a large number of ships, it is not sufficient simply to notice a collision risk, since it is difficult to take appropriate avoidance action if the operator does not also grasp the situation immediately. A collision risk index and a collision risk display system that were established to solve these problems are introduced in this section.

3.1.1 Establishment of Collision Risk Index

To establish a collision risk index based on the master / navigation officer's sense of collision risk, an approach consisting of three stages was implemented: first, "Digitalization of an experienced master / navigation officer's sense of risk," second, "Analysis of data on the sense of risk," and third, "Development of an algorithm for collision risk alarm." These three stages are explained below.

3.1.1.1 Digitalization of Experienced Master / navigation officer's Sense of Risk

An experienced master / navigation officer can operate a ship safely, even in congested waters, by appropriately understanding the situation. It is generally thought that the short-term memory capacity of humans is limited to about 4 to 5 pieces of information [1]. Given this limited memory capacity, the main components of the maritime skills required to ensure safe navigation are considered to include prioritization based on an appropriate sense of collision risk. Even assuming collision risk warnings are given to assist watches, the master / navigation officer may be confused by excessive information if multiple collision risk warnings are given without appropriately setting priorities in congested waters. To solve this problem, in this study, technological development was conducted with the aim of establishing a collision risk warning algorithm that assigns appropriate priorities by digitalizing the sense of collision risk of experienced masters / navigation officers.

First, data were prepared for the timing when risks are recognized, the types of ships recognized as risks and the level of risk. In digitalization, a tablet-type data acquisition system for the sense of risk (Fig. 4) was newly developed.

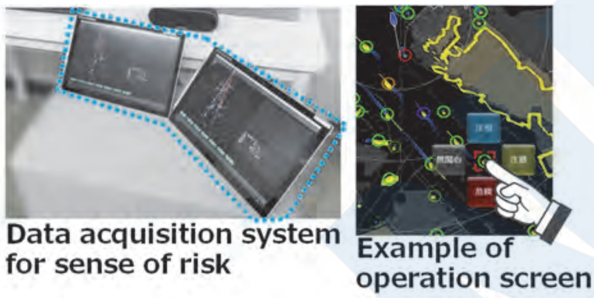


Figure 4 Developed data acquisition system for sense of risk

The data acquisition system for the sense of risk, which provides four risk levels, enables the user to enter the collision risk that the master / navigation officer senses in surrounding ships at the timing when the risk level changes. The definitions of the risk levels are shown below.

- Safe (no concern): No sense of risk in the subject ship.
- Close observation: Movement of the subject ship is observed occasionally.
- Attention: Movement of the subject ship is observed constantly.
- Dangerous: Action is taken to avoid the subject ship.

The risk level is set to "Safe" for a ship in the initial state, and one of the risk levels in the four stages above is always set for the subject ship.

Using the developed data acquisition system for the sense of risk, an experiment was conducted to acquire data on experienced master / navigation officers' sense of risk under various scenarios of navigation in congested waters in a simulated ship operation environment (reproduced in visual images from the bridge and on navigation devices at Japan Marine Science Inc.) (Fig. 5).

Figure 5 Experiment to acquire experienced masters / navigation officers' sense of risk

Table 1 shows the masters / navigation officers who participated in the experiment. In each fiscal year, multiple scenarios for congested waters such as the Kanmon Straits, Kii Channel and waters off the coast of the Oshima Island were used, and data on the sense of risk were acquired from a total of 20 people (16 captains, 3 first mates, 1 second mate).

Table 1 Crew with certificate of competency in seamanship who participated in data acquisition experiment for sense of risk

	FY 2016	FY 2017	FY 2018	Total
Captain	6 [persons]	6 [persons]	4 [persons]	16 [persons]
First mate	1 [person]	-	2 [persons]	3 [persons]
Second mate	1 [person]	-	-	1 [person]

3.1.1.2 Analysis of Sense of Risk Data

The following describes an analysis of the data on the sense of risk conducted to create an algorithm for the sense of collision risk of experienced masters / navigation officers. The analysis was carried out using a calculation model for the collision risk level [2] (bumper model) defined by the passing distance in the bow-stern direction and the port-starboard direction around the ship and the time to closest point of approach (TCPA). The distances (a, b and c) in the bow-stern direction and the port-starboard direction and the allowance time (weight) W_{tcpa} for the TCPA were considered as variable parameters, and the model geometries that best represent the individual masters / navigation officers' sense of collision risk were compared.

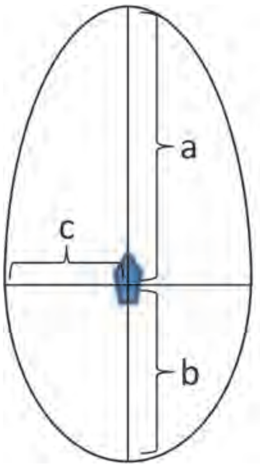
The rates of satisfying warning requests and satisfying non-warning requests are defined by formulas (1) and (2) below.

$$\text{Rate of satisfying warning request} = \frac{TP}{(TP+FN)}, \quad (1)$$

$$\text{Rate of satisfying non-warning request} = \frac{TN}{(TN+FP)}. \quad (2)$$

In Formula (1) and (2), TP, TN, FN, FP represents the combination patterns of the judgment by an experienced master / navigation officer and the result of the judgment based on the bumper model as below.

- If the judgment by an experienced master / navigation officer is "Attention" or higher, and the result of the judgment based on the bumper model is also "Attention" or higher: TP (True-Positive)
- If the judgment by an experienced master / navigation officer is "Close observation" or lower, and the result of the judgment based on the bumper model is also "Close observation" or lower: TN (True-Negative)
- If the judgment by an experienced master / navigation officer is "Attention" or higher, and the result of the judgment based on the bumper model is "Close observation" or lower: FN (False-Negative)
- If the judgment by an experienced master / navigation officer is "Close observation" or lower, and the result of the judgment based on the bumper model is "Attention" or higher: FP (False-Positive)



Parameter	Setting range
a. Distance in bow direction (NM)	0.9 to 2.1
b. Distance in stern direction (NM)	0.6 to 1.4
c. Distance in port-starboard direction (NM)	0.3 to 0.7
W_{tcpa} (min)	6 to 15

Figure 6 Bumper model and adjustment parameters

An ROC analysis (Receiver Operating Characteristic analysis) was conducted by plotting the values of the rates of satisfying warning requests and satisfying non-warning request obtained by formulas (1) and (2) while changing the adjustment parameters for the bumper model shown in Fig. 6. Since there were more than two variable parameters, a group of points on the outermost side from the origin (outermost points) was chosen from the points plotted on a two-dimensional plane of the rate of satisfying warning request and the/ -rate of satisfying non-warning request, as shown in Fig. 7, and was then used to draw an ROC curve. The ROC curve can be regarded as the results extracted from the parameter group adjusted by the bumper model so as to best represent an experienced master / navigation officer's sense of collision risk.

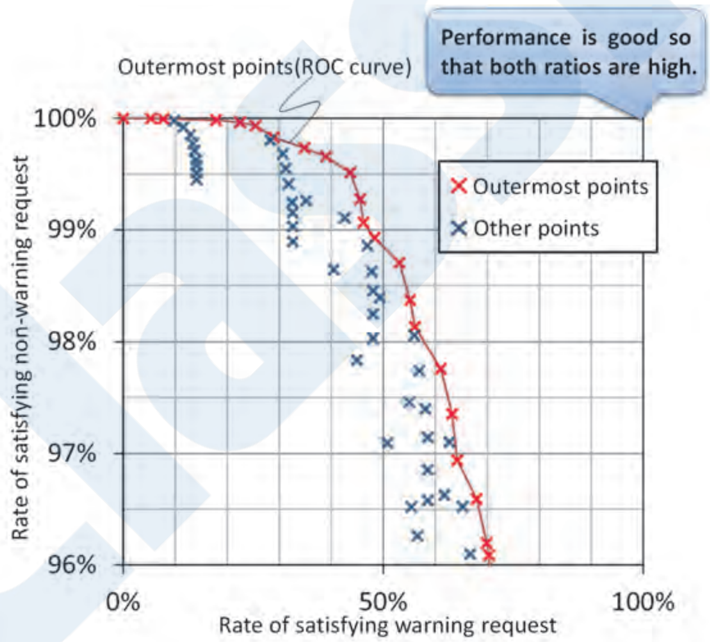


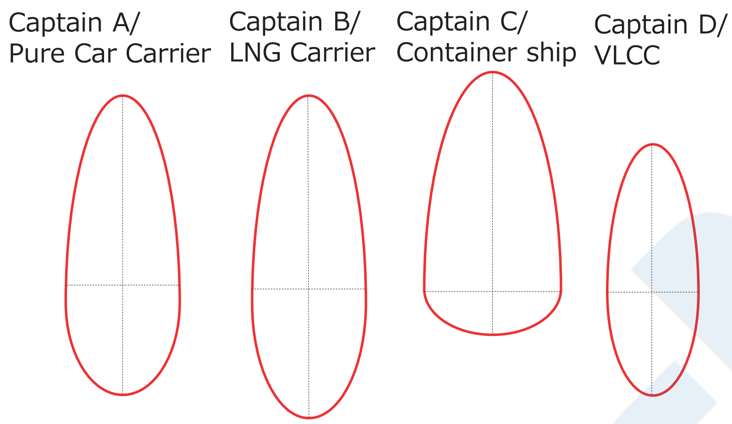
Figure 7 ROC curve

Figure 8 shows the bumper geometry for each master / navigation officer at the highest rate of satisfying warning requests in a range of rates of satisfying non-warning requests of 98 % or more. Figure 8 shows examples of the bumper geometries of the four captains, together with the different types of ships they operate. This result shows that the master / navigation officers' sense of collision risk includes many differences depending on the individual or ship type. The figure indicates that their senses of risk varied widely, especially for risk at the ship's stern. The results also indicated that some master / navigation officers, like captain D, may consider the entire bumper area to be small and the W_{tcpa} value to be short.

This result indicates that it will be necessary to construct a collision risk index as an algorithm that the user can adjust, while considering an algorithm reflecting the sense of collision risk of various masters / navigation officers depending on the individual sense and ship type, as well as variations in the sense of collision risk of the masters / navigation officers.

3.1.1.3 Development of Algorithm for Collision Risk Alarm

A new collision risk index was formulated based on the results of the analysis of the risk sense data described in the preceding section and a multifaceted analysis, and an algorithm for issuing alarms according to the risk of collision with another ship was established. In this algorithm, an alarm algorithm that can adapt to variations in the sense of risk of masters / navigation officers, as described in the preceding section, was selected by developing more advanced adjustment parameters. Figure 9 shows an example of the display screen of a warning system using the algorithm. The system achieves a warning function by presenting risk levels by OZT display and color/sound. The results of an evaluation with a simulator using the established algorithm are shown below.



	Bow [NM]	Stern [NM]	Port-starboard [NM]	W_{tcpa} [min]
Captain A	1.8	0.8	0.5	12
Captain B	1.8	1.2	0.5	12
Captain C	1.9	0.4	0.6	12
Captain D	1.3	0.9	0.4	7

Figure 8 Master / navigation officers' sense of risk (visualized using bumper model)

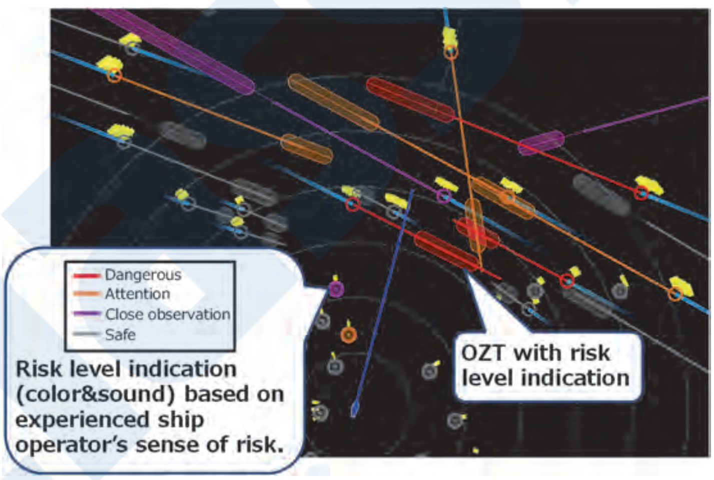


Figure 9 Warning system with risk levels and OZT display

Table 2 shows comments obtained in interviews with subjects who used the established warning system in a simulator test under congested water navigation scenarios. The comments are classified into positive and negative comments about the warning function. The positive comments show that the established warning system prevents overlooking risks and ensures recognition of changes in other ships' behaviors. The timing of issuing warnings was also rated highly. As negative comments, simply presenting the priorities of ships requiring attention by using risk levels did not completely prevent confusion of the master / navigation officer when the system was used in congested waters where a number of ships requiring attention can be seen.

Table 2 Evaluation and comments on collision risk warning algorithm

Positive/Negative	Content of comment
Positive	• In this scenario, the areas where the ship can navigate are limited so strictly that the master / navigation officer has no choice but to pass the acceptable area. The situation will not change even if a warning is issued, but a warning is necessary because it makes it possible to prepare ourselves. (Captain A) • The system made me aware of a target that became dangerous due to an abrupt slowdown. (Captain B) • A CPA warning is a scenario in which an alarm should be sounded continuously, but the new warning was issued appropriately (first mate D, third mate F). • The system made me aware of a meeting vessel that I overlooked in visual watch (junior third mate G, junior third mate H). • The system made me aware of a heading change by another ship. (Captain I, Captain J)
Negative	• So many targets are described as “Danger” or “Requiring attention” that the situation sometimes exceeded my cognition ability. (first mate E) • If the number of “Close observation” targets increases, it is difficult to understand. The risk level “Close observation” may be unnecessary. (first mate D)

3.1.2 Establishment of Collision Risk Indication

The results of the evaluation of the collision risk warning algorithm described in the preceding section indicated a weakness in the support function for understanding the surroundings in congested waters if only the risk level for each ship is presented. Therefore, an indication function was established to compensate for this weakness.

In the situation shown in Fig. 9, the large number of ships requiring attention confused the master / navigation officer. As shown in Fig. 9, the risk level for the target ship is displayed in the same color as the OZT display color, but in congested waters like those in this experiment, a large number of ships other than safe ships are displayed simultaneously. Therefore, the display system was unsuitable for studying how to avoid collisions with these many ships.

To solve this problem, the following improvements were made in the collision risk indication.

① For the width of the OZT display (perpendicular direction from the course of another ship), the display area is expanded, and the apex of the obstacle zone is set at the ship’s position at which the other ship passes safely at an arbitrary distance in the ship’s bow direction, or the ship’s position at which the other ship passes safely at an arbitrary distance in the ship’s stern direction (Fig. 10).

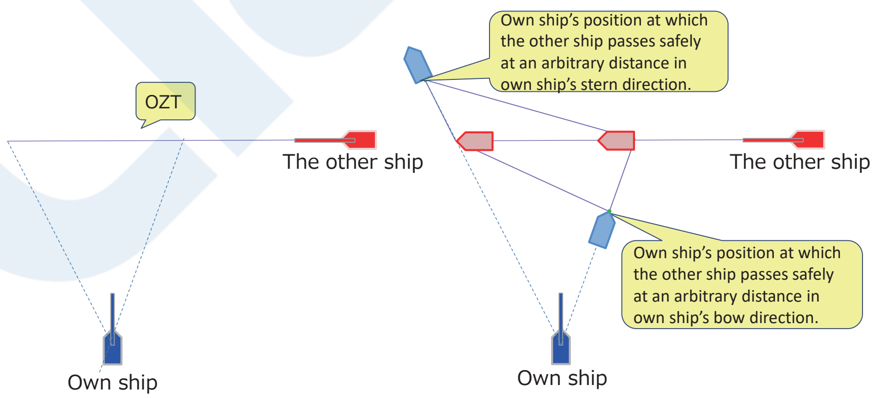


Figure 10 Expansion of display

② The zone calculation in ① is executed with two distance settings, the distance at which to keep watch for any approach to the ship and the hull length of the own ship and another ship, and the two obtained zones are expressed as the approach zone and the collision zone, respectively (Fig. 11).

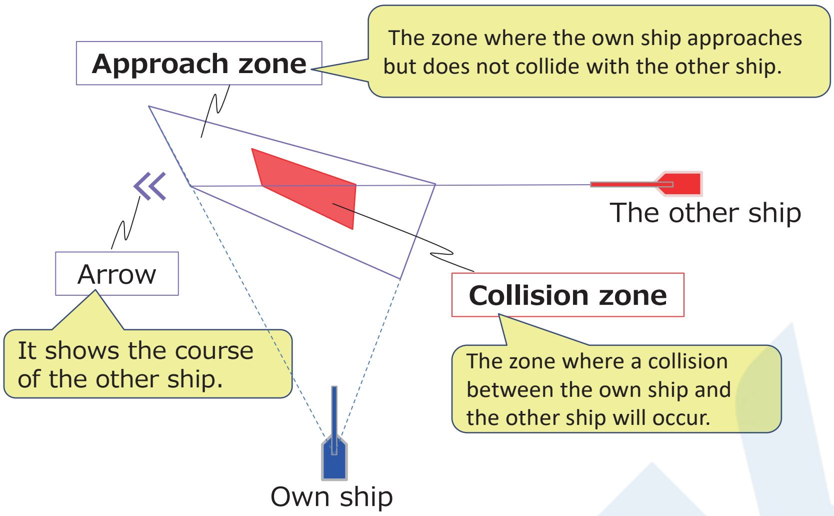


Figure 11　Display of collision risk indications (approach zone and collision zone)

③　The risk levels are indicated by the icon of the other ship and the color of the collision zone.

These improvements enable a separate display of the zone where a collision between the own ship and the other ship will occur (collision zone) and the zone where the own ship approaches but does not collide with the other ship (approach zone). The collision risk level is indicated by the collision zone display color so that a route can be selected while considering the approach zone caused by multiple ships from a panoramic point of view. The collision risk levels of individual ships are indicated in collision zone display colors that are shown for relatively small zone as a support function for prevention of overlooking individual ships subject to collision risk warnings and collision avoidance decisions.

Figure 12 shows an example of a display of the collision risk indications established in this project. In comparison with the collision risk levels indicated by the OZT display colors in Fig. 9, the system indicates fewer areas where “navigation seems impossible” according to display zone. The collision risk level display also sufficiently represents the collision risks for individual ships. As indicated by the red broken line in the figure, by using the display, the user can easily locate areas which are congested with ships by viewing the collision risk indications caused by multiple ships from a panoramic perspective. Areas with fewer collision risk indications can also be grasped easily, as indicated by the yellow broken line in the figure. This has made it possible to provide, at an early timing, not only the information necessary for avoiding collisions with individual ships, but also the information necessary for selecting routes for the risks that will be encountered in the future.

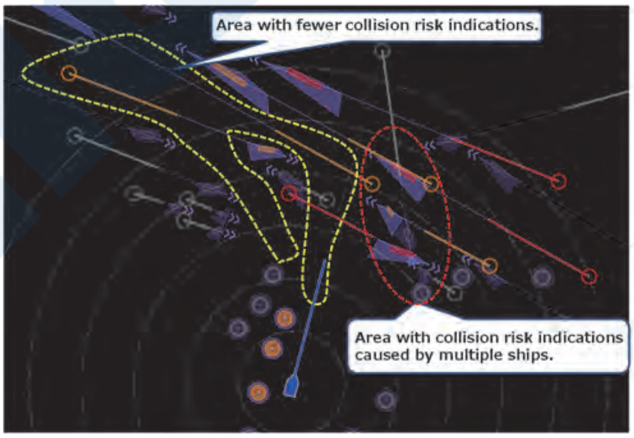


Figure 12　Collision risk indications established for this system

3.1.3　Summary of Efforts by Furuno Electric Co., Ltd.

This section 3.1 has introduced an overview of the collision risk index and collision risk indication developed by Furuno Electric. This high effectiveness of this technology in supporting decision-making for ship operation has already been confirmed through a number of simulation tests, and it is expected that the number of ship collisions will decrease and the burden of watch duties will be reduced. In the future, the company is targeting practical application of this technology as a "collision warning function and collision avoidance support display function" after conducting a demonstration experiment in which master / navigation officers will evaluate the technology using real ships and demonstrating compliance with the Guidelines for Safe Design of Automated Ship Operation to improve the effectiveness and practicability of the functions.

3.2 Technological Development by JRC

3.2.1 Collision Risk Index

JRC studied a collision risk index that matches the sense of risk of actual navigation officers to replace DCPA/TCPA based on "Nagasawa's collision risk levels" [2]. In Nagasawa's collision risk levels, the passing distance with other ship that the master / navigation officer judges as safe is defined by an elliptic area, as shown in Fig. 13. The size of this ellipse (minor radius a, major radius b) and the distances in the bow-stern direction and the port-starboard direction are represented as functions using the length, speed and course of own and other ship as parameters. Since it is thought that failure to secure this passing distance will place a psychological burden on the master / navigation officer, the risk level is calculated based on the magnitude of the intrusion level.

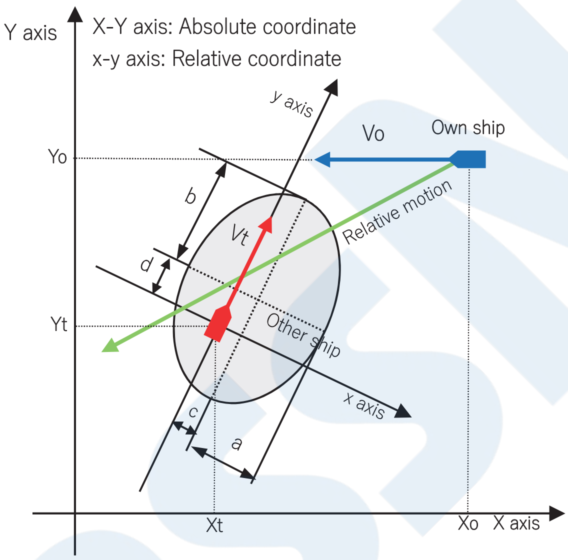


Figure 13　Concept of safe passing distance

a, b, c, d: Passing distance parameters
Vo: Speed of own ship (m/s)
Vt: Speed of other ship (m/s)

For the collision risk index R, the values of the risk levels ***Rx*** and ***Ry*** in the port-starboard direction and the bow-stern direction, respectively, from the intersection point between the x-y coordinate axis and the relative motion vector around the other ship are found, as shown in Fig.14, and the larger value is adopted as the risk level. To evaluate the time-based allowance, weighting is performed by using the ratio of the time to the closest point of approach (*Tcpa*) to a certain allowance time (*Wtcpa*).

$$\text{Collision risk index } \boldsymbol{R} = Max\left(Rx,\ \ Ry\right) \times \left(1 - \frac{Tcpa}{Wtcpa}\right) \geq 0$$

Tcpa: Time to closest point of approach
Wtcpa: Allowance time (weighting factor)

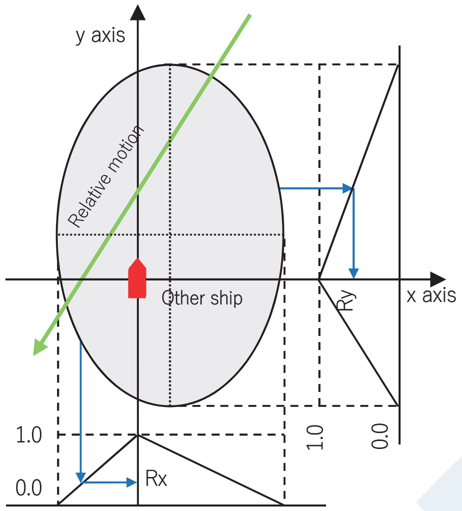


Figure 14　Collision risk index calculation model

Based on this index, the parameters for calculating the collision risk index were adjusted using data on collision risk judgment collected from master / navigation officers in a ship operation simulation test and the results of interviews conducted after the test.

Since the collision risk index is represented by a numerical value from 0.0 to 1.0 (where 1.0 represents the most dangerous situation), the thresholds shown in Fig. 15 are set, and the master / navigation officer is notified of the collision risk by using the following three levels.

- Danger (D): A ship that immediately requires collision avoidance navigation.
- Warning (W): A ship that requires caution as a ship that does not require immediate collision avoidance navigation, but may require action in the future.
- Safe (S): Ships other than the above.

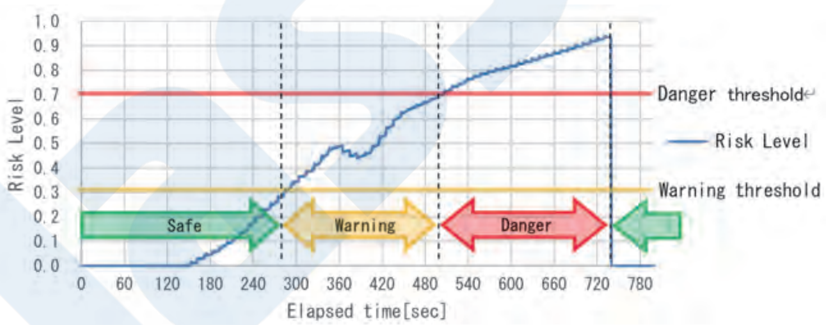


Figure 15　Concept of thresholds

In this way, the results of judgments on other ships by the collision risk index are used to issue warnings concerning dangerous ships and ships requiring caution. The results of these judgments are represented by the symbol color of the AIS target, as shown in Table 3.

Table 3　Method for displaying risk level judgments

Risk level	Identification number	Symbol color	Effect	Example of display
Danger	D + target number	Red	Blinking	
Warning	W + target number	Orange	Blinking	
Safe	S + target number	Green	None	

A prototype was developed to verify the effect of the collision risk index. The index was incorporated in the radar system, which is a typical support device for collision avoidance. The results of the ship operation simulation test confirmed that the Danger and Warning alerts expressed by the collision risk index were closer to the navigation officers' sense of risk than DCPA/TCPA for ships approaching in various encounter situations where collision was possible.

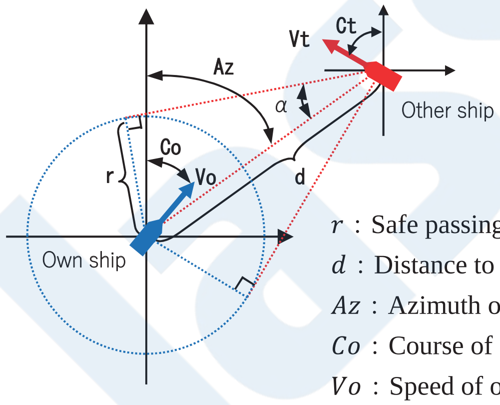
Study of the practical application of this collision risk index will be necessary in the future. Although the collision risk index was incorporated in the radar system as the prototype, IMO rules require the use DCPA/TCPA alarms in radar. Thus, incorporation of the collision risk index in radar appears to be difficult under these circumstances. To enable early practical use, it will be necessary to consider incorporating the index in a device which is not subject to the above-mentioned IMO requirement. Since it is thought that a collision avoidance navigation support system that integrates data acquired by cameras and the like in addition to a radar and AIS will be developed for autonomous ship in the future, it is desirable to study practical application of the index in that type of integrated target display device.

3.2.2 Collision Risk Area

For the display method of the collision risk area, we first considered using OZT (Obstacle Zone by Target) [3], which was devised by Professor Emeritus Imazu Hayama of Tokyo University of Marine Science and Technology. OZT indicates a course where the navigation of a ship may be obstructed by other ship. Here, it means the area in which the distance to other ship is within the minimum safe passing distance r, that is, when the distance to closest point of approach (DCPA) of the other ship satisfies the following condition.

$$DCPA \leq r$$

A course in which $DCPA = r$ between own ship and other ship is defined as a collision course Co. The method of calculating the collision course is shown in Fig. 16.



r : Safe passing distance
d : Distance to other ship
Az : Azimuth of other ship
Co : Course of own ship (collision course)
Vo : Speed of own ship
Ct : Course of other ship
Vt : Speed of other ship
α : Angle of the tangent
($\alpha = \sin^{-1} r/d$) (3)

Figure 16 Collision course calculation diagram

In the above variable, the following relation formula holds.

$$\frac{\sin(Az \pm \alpha - Co)}{Vt} = \frac{\sin(Az \pm \alpha - Ct)}{Vo}$$

Based on this, a collision course Co in which $DCPA = r$ can calculate as follows.

$$Co \;= Az \pm \alpha - \sin^{-1}\left\{\frac{Vt}{Vo}\sin(Az \pm \alpha - Ct)\right\} \quad (4)$$

The dangerous courses (OZT) in which $DCPA \leq r$, as shown in Fig. 17, is within an area between the collision courses $Co_{+\alpha}$ and $Co_{-\alpha}$, which are found when $+\alpha$ and $-\alpha$ are given in formula (4).

The collision point is also found so as to identify the most dangerous course. Since the safe passing distance for the course to the collision point is $r = 0$, $\alpha = 0$ is found from formula (3), and $Co_{\alpha=0}$ is calculated by assigning this in formula (4) (the value of $Co_{\alpha=0}$ will be between $Co_{+\alpha}$ and $Co_{-\alpha}$).

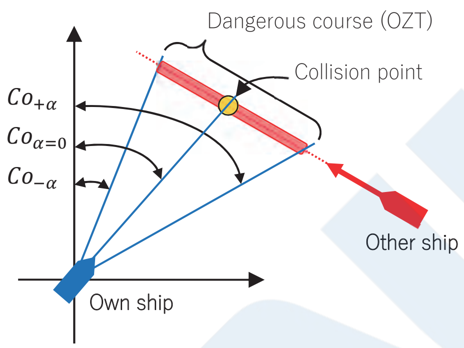


Figure 17 Range of dangerous courses (OZT) and collision point

The master / navigation officer can navigate while securing safe passing distance r to other ship by operating the ship in such a manner that own course does not intersect with the dangerous course defined by the OZT.

While the dangerous course (OZT) is an index in own direction of the ship's course, next, we considered displaying the collision risk area two-dimensionally in the course and distance directions. As shown in Fig. 18, the rhomboidal area with vertexes in the anteroposterior and crosswise directions of the ship is defined as the safe passing area, and the area where other ship enters this area is calculated. The distances to the vertexes (a, b, c and d) can be changed according to the area of navigation.

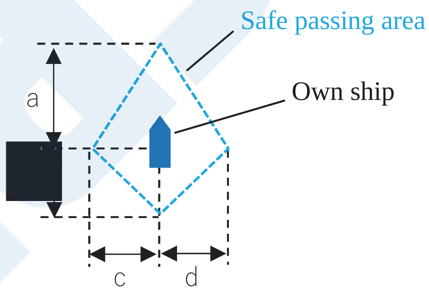


Figure 18 Safe passing area

In calculating the dangerous area, formula (4) is used first to calculate a point on the safe passing area and the point at which the ship collides with other ship, as shown in Fig. 19. Subsequently, this collision point is shifted by a distance corresponding to the safe passing area to the position of the ship. This calculation is performed for all points on the safe passing area. This step is performed repeatedly while changing own course, and only the points in own course direction of the ship are used. Thus, a dangerous area can be calculated.

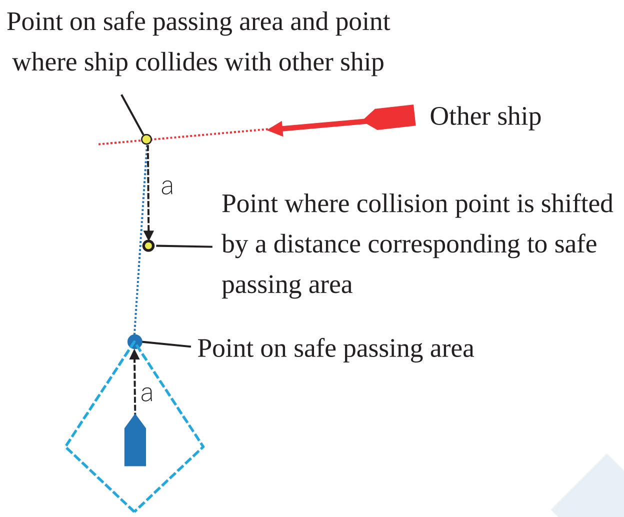


Figure 19 Method of calculating dangerous area

Figure 20 shows an example of a calculation of a dangerous area. This example shows the dangerous area when the speed of the ship is the same as that of the other ship and the course of the target ship is 225°. The master / navigation officer can navigate while securing the safe passing distance shown in Fig. 18 between the own ship and other ship by operating own ship so that it does not enter the dangerous area.

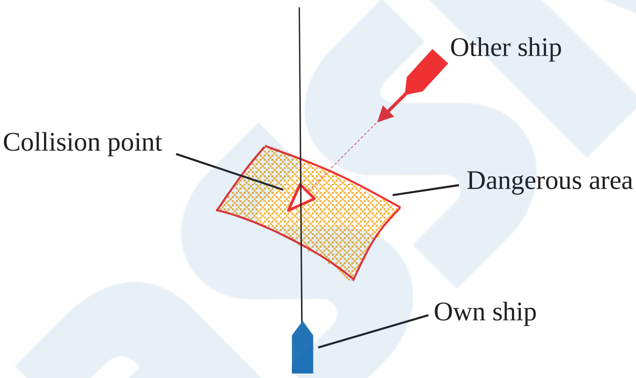


Figure 20 Example of calculation of dangerous area

Figure 21 shows the positions of the own ship and other ship in a situation where the own ship reaches the vertex of the dangerous area. With a dangerous course (OZT), it is only possible to show which course other ship enters the safe passing distance if own ship advances toward the dangerous course. However, with a dangerous area, not only the course, but also the distance that other ship enters the safe passing area becomes clear.

It is thought that dangerous area allows the master / navigation officer to clearly recognize the area where the ship can safety navigate. As an additional advantage, since the dangerous area represents the area that should be avoided as a plane, the route on which the ship can navigate can be seen more clearly than in the case of the dangerous course.

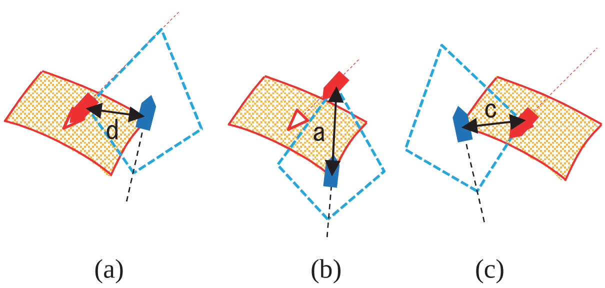


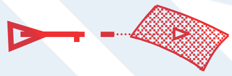
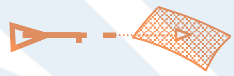
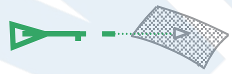
Figure 21 Distance to other ship at vertex of dangerous area

To summarize the foregoing discussion, the meanings of the dangerous course (OZT), the dangerous area and the collision point are as follows.

[Dangerous course]
If own ship advances in the indicated direction, other ship will enter the safe passing distance.
[Dangerous area]
If own ship enters the indicated area, other ship enters the safe passing distance.
[Collision point]
If own ship advances in the indicated direction, it will collide with other ship.

Table 4 shows the method for displaying a dangerous course (OZT) and a dangerous area. The colors are changed according to the results of the risk level judgment using the collision risk index.

Table 4　Method for displaying dangerous course/dangerous area

Risk level	Color	Dangerous course	Dangerous area
Danger	Red		
Warning	Orange		
Safe	Gray		

In the display of a dangerous course, the shape is an arrow and course of other ship is indicated with the direction of an arrow. By contrast, in the display of a dangerous area, it is difficult to express the direction by the shape of the area itself. Therefore, the shape of the collision point is expressed by a triangle, and the course of other ship is indicated by the direction of this triangle.

Figure 22 shows an example of a dangerous course displayed on the actual radar screen, while Fig. 23 shows an example of a dangerous area displayed on the screen. The two figures show the same situation, and the dangerous course shown in Fig. 22 is expanded to a two-dimensional area in Fig. 23. This enables the master / navigation officer not only to confirm the course, but also to recognize how far other ship will enter the safe passing area.

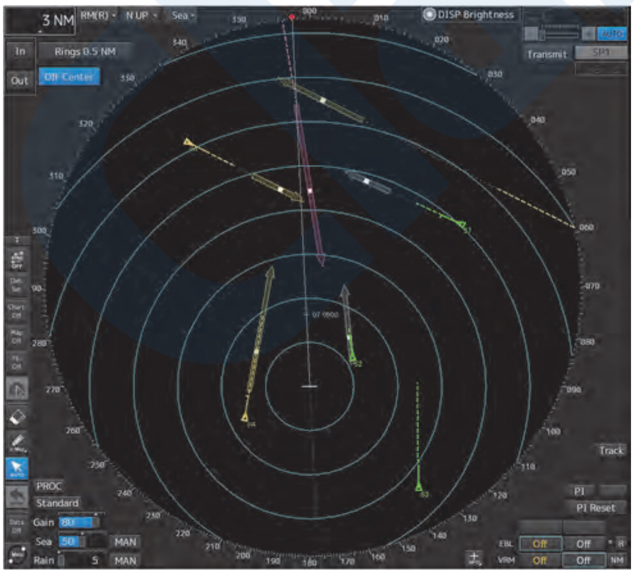


Figure 22　Example of dangerous course display

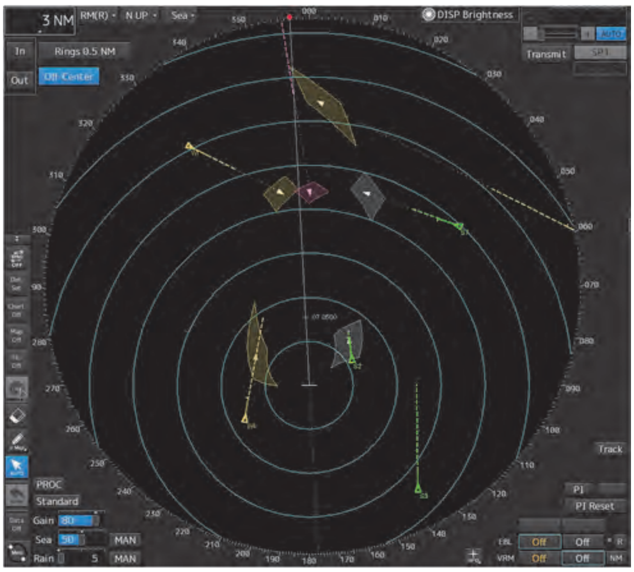


Figure 23　Example of dangerous area display

As with the collision risk index, a prototype for displaying the collision risk area was incorporated in the radar, and a ship operation simulation test was conducted to confirm its effect. The test was conducted for a dangerous course and a dangerous area using the same scenario. It was found that the display is highly effective, as the frequency of collisions with other ships was much smaller than without the display. Although there was not a large difference between the dangerous course and the dangerous area, many master / navigation officers reported that it was easier to find a collision avoidance route with the dangerous area display. However, some operators commented that the dangerous areas overlapped in cases where many ships were present, resulting in a complicated display that was difficult to see.

We will also study practical application of the collision risk area display in the future. Since this function, like the collision risk index, is intended to prevent collisions, it is considered most appropriate to incorporate the function in the radar. Unlike the collision risk index, the display of a collision risk area is not a function which is required by rules. Therefore, incorporation of this function in the radar as an additional function for practical use is considered possible. Moreover, because this function will also be effective for ECDIS, which plays an important role in determining the ship’s route, it is necessary to consider incorporating the function in the ECDIS system. In addition, this function is also considered to be an essential technology for providing collision avoidance routes in collision avoidance support devices intended for automatic navigation.

3.3 Technological Development by Tokyo Keiki Inc.

3.3.1 Collision Risk Index

Referring to the existing indexes, Tokyo Keiki developed “normalized CPA risk” as a collision risk index based on DCPA/TCPA in which DCPA and TCPA are each normalized with a weighting factor W. (Note: The indexes are divided by W, and the value range is converted to 0 to 1.) The results are then subtracted from 1 and multiplied together to obtain a risk level in a range of 0 to 1 (see Fig. 24). If the original value is larger than W, the normalized value is regarded as 1.

This index is intended to be closer to the sense of master / navigation officers by varying the weighting factor according to the encounter situation, while keeping a simple composition based on CPA information, which is familiar to master / navigation officers.

$$\text{Normalized CPA Risk} = \left(1 - \underbrace{\frac{DCPA}{W_{dcpa}}}_{\text{Normalized DCPA}}\right) * \left(1 - \underbrace{\frac{TCPA}{W_{tcpa}}}_{\text{Normalized TCPA}}\right)$$

DCPA : Distance of CPA, W_{dcpa} : weighting factor (>0)
TCPA : Time to CPA, W_{tcpa} : weighting factor (>0)

Figure 24 Calculation formula for normalized CPA risk

The weighting factors of DCPA/TCPA are explained below. The weighting factor of DCPA (W_{dcpa}) is set on the basis of a circular safe passing area that is assumed to exist around the ship. The weighting factor of TCPA (W_{tcpa}) is varied according to the angle of encounter with another ship, which can be considered to be a characteristic feature of this index. In concrete terms, when a ship is in a situation of possible collision with another ship, the TCPA at the time when “the course change angle for safely avoiding the other ship by securing a certain distance regardless of the encounter situation is the same (in other words, the range of the dangerous courses is the same)” is calculated for each encounter situations, and W_{tcpa} is set based on a graph connecting the results (see Fig. 25).

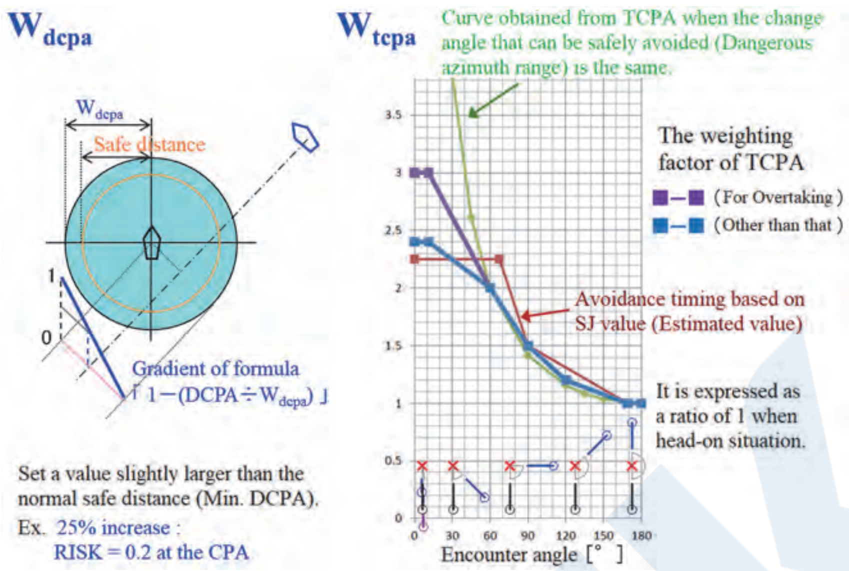


Figure 25　Weighting factors for normalized CPA risk

Looking at the range of dangerous courses (i.e., the course change angle for collision avoidance) when the normalized CPA risk set using the weighting factors as described above had almost the same value in encounter situations with the same DCPA and different TCPA, the value was almost the same regardless of the encounter situation, as was expected (see Fig. 26).

On the right side of the figure shown below, the range of dangerous courses is expressed by using DAC, which is described later. The graph at the lower left represents a "normalized CPA coordinate system," in which the normalized DCPA values and normalized TCPA values are plotted on the abscissa and the ordinate, respectively, and the multiple curves in the coordinate system are the "risk level curves" that are obtained by modifying the normalized CPA risk formula. In this coordinate system, the upper right part represents a safe state, and the lower left part is a dangerous state. Therefore, if the normalized values for each of the other ships are plotted, application of this index to prioritization of actions when responding to other ships can be expected.

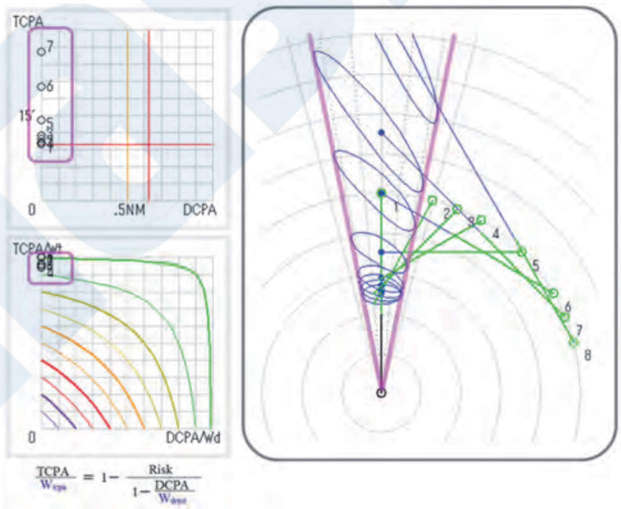


Figure 26　Example in which normalized CPA risk substantially coincides with range of dangerous courses

Comparing the set W_{tcpa} graph and the TCPA at the time of collision avoidance based on the SJ value (subjective judgment of collision risk level) corresponding to the angle of encounter, the two show very similar trends (see the graph at the right in Fig. 25). Therefore, the W_{tcpa} setting method described above is considered to fulfill the purpose of creating this index, which is "to be closer to the sense of master / navigation officers."

Validation and study for further improvement of the normalized CPA risk index are currently in progress. In the future, the company aims to achieve the following uses of the index by incorporating normalized CPA risk in radar, ECDIS/ECS, *etc.*

- Risk level display (numerical value, time series graph)
- Color coding of attributes for display of other ships according to the risk level
- Issuance of alarms according to the risk level
- Identification of the status of other ships based on the normalized CPA coordinate system
- Application to the risk level in the collision avoidance algorithm

A patent application for normalized CPA risk has already been submitted.

3.3.2 Collision Risk Area

Since the 1970s, Tokyo Keiki has provided functions for displaying "collision areas" such as PAD (Predicted Area of Danger) and DAC (Dangerous Area of Collision) in radar, as shown in Fig. 27.

Figure 27 Tokyo Keiki products incorporating "collision area" display functions

In PAD, as shown in Fig. 28, a range of dangerous courses when another ship approaches the ship inside the safe passing distance that should be secured is set on the true course of the other ship, and the depth perpendicular to the other ship's course is expressed by an ellipse or a hexagon, which is assumed to represent the safe passing distance.

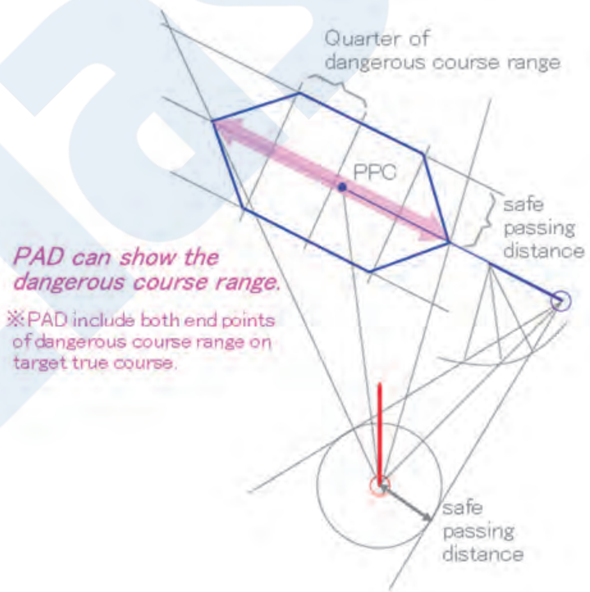


Figure 28 Principle of PAD (case of hexagonal PAD)

In contrast, as shown in Fig. 29, DAC accurately displays the danger area where another ship approaches the ship inside the safe passing distance by calculating the vertexes of the "safe passing area," which approximates a circle with its radius representing the safe passing distance as a polygon (① to ⑧ in the figure), and the point of collision with the other ship, using the ship's positions when the vertexes collide (①' to ⑧' in the figure) as component points.

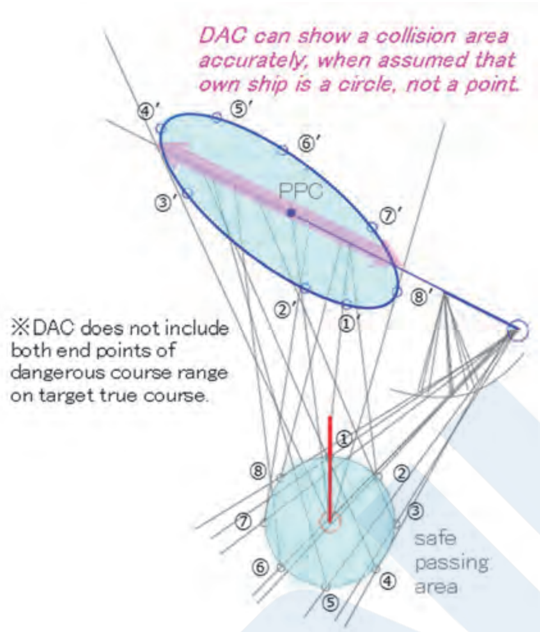


Figure 29 Principle of DAC (case of octagonal DAC)

It is not easy to accurately find a collision avoidance course change angle at which a safe passing distance can be secured from information based on the conventional closest point of approach method, even in simple encounter situations. For example, in Fig. 30 (left), the display shows that the ship passes the stern of a ship passing in front of it by steering to the right, but the course change required to secure the necessary passing distance is not immediately apparent. However, since a "collision area" such as DAC can accurately indicate the range of dangerous courses, the master / navigation officer can determine the necessary course change on the screen, as shown Fig. 30 (right). [4)]

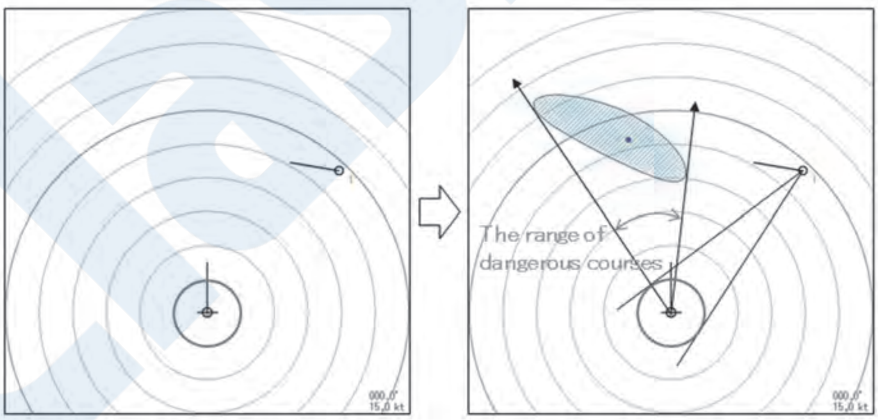


Figure 30 Identification of the range of dangerous courses in DAC display

Furthermore, DAC not only enables the master / navigation officer to confirm the range of dangerous courses in the same manner as with PAD, but can also accurately display the depth direction (direction perpendicular to the direction of the true motion of another ship). Therefore, even if another ship enters the safe passing area, DAC can continue to display the ship and estimate the following:

① How soon the other ship will enter the area
② How long the other ship will travel in the area
③ When the other ship will leave the safe passing area

In Fig. 31, the numbers ① to ③ and ①’ to ③’ represent the ranges of the above items and the range corresponding to numbers ① to ③ on the relative motion line, respectively.

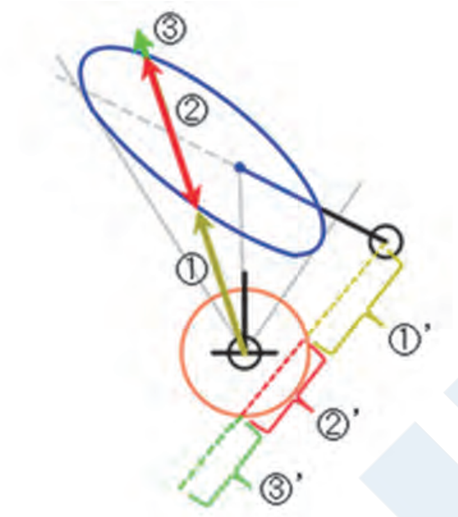
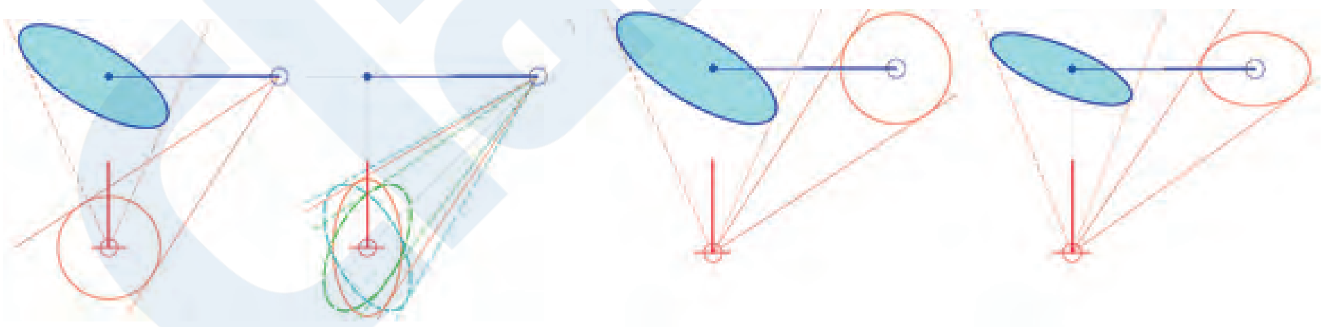


Figure 31　Depth information of DAC

In the conventional DAC, a safe passing area was set as a perfect circular shape around the ship (Fig. 32 (a)), but according to findings of marine traffic engineering, the actual shape of such a passing area should be an ellipse which is elongated in the travel direction and narrower in the lateral direction. However, if an elliptic area was set around own ship with the conventional DAC, the range of dangerous courses will change depending on the direction of own ship, and as a result, DAC will lose its key features of “safety without trial ship operation/possible to understand dangerous courses at a glance.” Therefore, this setting was not realized (Fig. 32 (b)).

To solve this problem, a new method for setting the safe passing area around another ship was devised. If the shape is a perfect circle, the displayed shape, size and position of the DAC are the same as those of the area set around own ship (Fig. 32 (c)). Further, if the shape is elliptic, the problem that the range of dangerous courses changes depending on the direction of own ship does not occur (Fig. 32 (d)). It also became possible to shift the center of the area from the position of another ship (offset). A Japanese patent has already been granted for this new DAC method, and foreign patents are pending.



(a)　(b)　(c)　(d)

Figure 32　Change of placement of safe passing area with DAC

In the existing product shown in Fig. 27, PAD and DAC were line drawings due to the limitation of computer drawing processing capability. However, recent PCs have significantly improved drawing capabilities and are capable of displaying the “collision area” more graphically. Figures 33 and 34 show the comparison of a line drawing and a 2D drawing of DAC. Thus, a new display method which improves the visibility of DAC is under development, and implementation in devices such as radar and ECDIS is planned in the future.

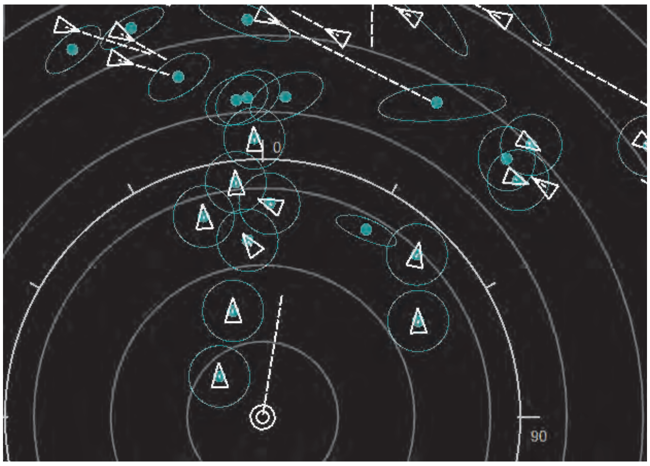


Figure 33 Example of DAC display (line drawing)

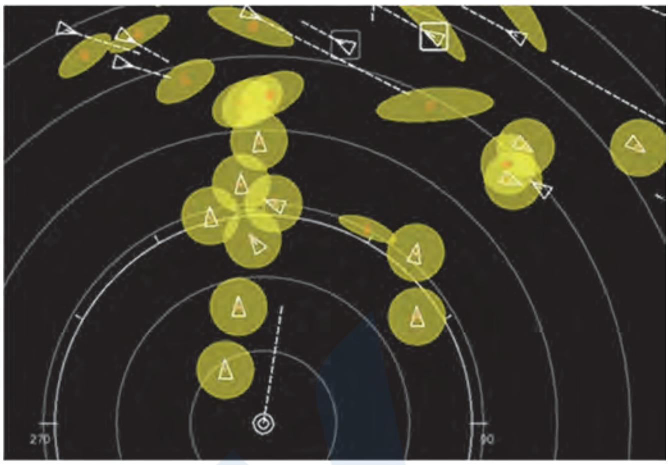


Figure 34 Example of DAC display (transparent fill)

Recently, navigation support information has also become available via the internet using mobile devices such as smartphones and tablet terminals. “Aisea” (https://aisea.net/), which is operated by Aidea Inc., is an example of this type of system. In cooperation with Aidea Inc., Tokyo Keiki developed a new version of DAC with the aim of incorporating a DAC display function into “Aisea PRO,” which is a corporate-type application platform, and an updated version of DAC including this function was released in August 2020. Figure 35 shows an example of a DAC display on the “Aisea PRO” screen.

“Aisea PRO” is capable of displaying areas with a risk of collision with other ships in red, yellow and blue in the order of risk levels. The aims of this function are to reduce the burden on the master / navigation officer and realize support for decision-making in ship operation for collision avoidance.

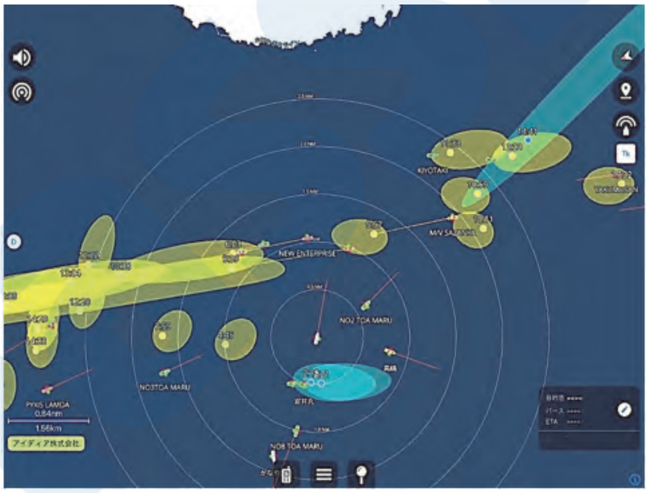


Figure 35 Example of DAC display on “Aisea PRO”

Tokyo Keiki also concluded a business intermediary contract and service outsourcing contract with Aidea Inc. for sales of “Aisea PRO” and started this business in January 2021. Tokyo Keiki will work to contribute to safer navigation and higher efficiency in operation management by promoting wide adoption of “Aisea PRO.”

4. VERIFICATION OF EFFECT OF COLLISION RISK INDEXES AND COLLISION RISK AREAS

A ship handling experiment using a ship handling simulator was conducted in order to objectively and quantitatively evaluate the effectiveness of the collision risk indexes (alarms by colors or sounds) developed by Furuno Electric, Japan Radio and Tokyo Keiki based on data on the sense of risk of experienced master / navigation officers collected in this study, and the collision risk area display, which visualizes the basis for the risk indexes. This section presents an outline of the ship handling experiment and details of the results of a quantitative evaluation of the findings from ship handling operation by using the track charts and a ship handling evaluation program.

4.1 Simulator Experiment

4.1.1 Outline of Experiment

Using a scenario that assumed congested waters, a comparative evaluation was conducted for a case where the subjects performed normal ship handling based on information collected by radar (without support) and a case where the subjects performed ship handling using a ship operation support device that displayed collision risk indexes/areas under the same scenario (with support). As the comparative verification method, the track charts were compared, and a ship handling evaluation program owned by Japan Marine Science was used.

This experiment was conducted during a period from 2019 to 2020 with subjects having varied levels of experience, ranging from captains with extensive experience in operating ocean-going ships to junior navigation officers and cadets (students belonging to maritime education institutes). This subsection introduces the result of an experiment with cadets that was conducted in 2020 using an established evaluation method. As an example of the results of a typical experiment, the following introduces the results of an experiment using a ship operation support device created by Furuno Electric.

4.1.2 Experimental Scenario

The scenario used in the evaluation of the experiment assumed a large containership operating in the congested waters around Singapore, in which the ship enters the sea lane while the master / navigation officer observes the situation of passing ships. The outline of the ship and the scenario chart are presented below. (In Fig. 36, the red track represents the ship's track regarded as ideal.)

Table 5 Outline of ship used in experiment

Outline of ship used in experiment	
Ship type	Containership (9100 TEU)
Ship model (L/B/d)	349.8 m/45.6 m/14.5 m
Set speed	12 kt (S/B Full)

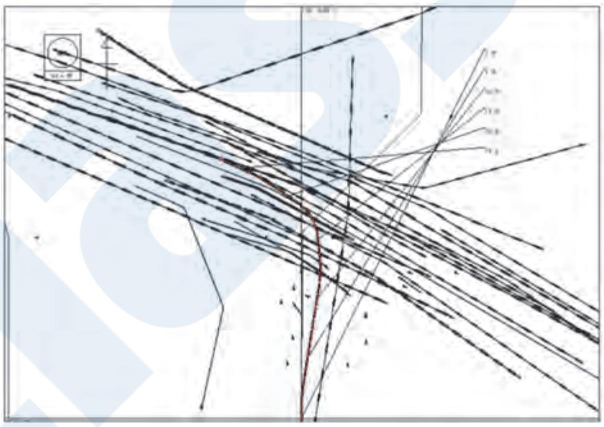


Figure 36 Outline of scenario used in experiment

As the precondition for this experiment, the speed (engine power) of the ship was set to a constant condition and ship operation for collision avoidance was performed using only the rudder so that changes in the encounter situation resulting from changes in the speed of the ship would not affect the comparative verification.

4.1.3 Evaluation Method

As the method for objectively and quantitatively evaluating the effectiveness of the collision risk indexes/area display, track charts and a ship handling evaluation program were used.

In the evaluation using the track charts, a comparative verification was conducted by overlapping the tracks of multiple ships on a gridded sheet and analyzing the variations in the tracks. The size of the adopted grid was 500 meters square, which was based on the results of interviews with master / navigation officers, who reported that the passing distance with another ship that the master / navigation officer should secure in congested waters is approximately 2.5 to 3 cables (approx. 500 m).

In the evaluation using the ship handling evaluation program, the “Auto Grading System” (hereinafter abbreviated “AGS”) owned by Japan Marine Science was adopted. AGS is software which is provided with a ship handling simulator made by Japan Marine Science and is capable of expressing ship handling results by scores based on a quantitative evaluation of the results of various evaluation items, such as encounter situations with other ships, buoys, rocks and other marine obstacles and no-go areas (NGA).

The basic evaluation formula for the ship handling results with AGS is intended to produce a result based on non-dimensional negative scores by dividing the dangerous area entry time for each evaluation item by the ship operation time.

$$Score = -\frac{x * t_{Dangerous} + y * t_{Caution}}{t_{end}} *$$

where,

Score: Evaluation score

$t_{Dangerous}$: Period/time in Dangerous area (s)

$t_{Caution}$: Period/time in Caution area (s)

x: Variable for Dangerous area for weighting

y: Variable for Caution area for weighting

t_{End}: Period/time of ship maneuvering (s)

A result in which a ship operation accident occurs (called a “Consequence” in this system) and the degrees of violations of safety constraints such as entering a NGA in the process leading to that result were arranged hierarchically, as shown in Fig. 37, and weights were assigned to each item.

Figure 37 Degrees of violations of safety constraints

AGS is intended to evaluate any ship handling action that may lead to a ship operation accident. Therefore, for “Consequence,” which is the top-ranked degree of violation in Fig. 37, the system detects and displays the event but does not evaluate it. Accordingly, the evaluation items are the levels “Approaching to Safety Constraint” and “Process to Approaching Safety Constraint.” Table 6 shows the result of classifying the evaluation items as described above. The weighting factors (Wf) for the two levels below “Safety Constraint” are 2 for the higher level items and 1 for the lower.

Table 6 AGS evaluation items and weighting factors (Wf)

Id	Layer	Items	Wf.
1	Consequence (accident)	Collision	n/a
2		Grounding	n/a
3	Approaching to Safety Constraint (To Object)	Relationship with other ship (distance and heading change rate)	2
4		Relationship with other ship (e.g., fishing boat)	2
5		Buoy passing distance	2

6		Passing distance of an arbitrary point	2
7		Deceleration in docking	2
8	Approaching to Safety Constraint (To Area)	NGA entry	2
9		Navigation outside designated course	2
10	Process to Approaching Safety Constraint	ROT limit	1
11		Speed limit in course	1
12	Other (Economy)	Economic operation index	n/a

This evaluation program contains an evaluation formula [5] based on a "Dangerous area chart" in evaluations of the relationship with other ships. The method uses the relative distance and the rate of bearing change when another ship passes as indexes, and is capable of evaluating when another ship passes with a very fine mesh of 1 s. Its validity has been established based on a background of many years of research.

4.2 Results of Experiment

4.2.1 Evaluation and Analysis Using Track Charts

Figure 38 shows the results of ship handling by 15 subjects in the form of track charts. The track chart at the left is the result of normal ship handling (without support), and that at the right is the result of ship handling under the same scenario using a ship operation support device (with support). The blue tracks are "tracks of navigation without collision," and the red tracks are "tracks with collision" or "tracks of reverse navigation on the course."

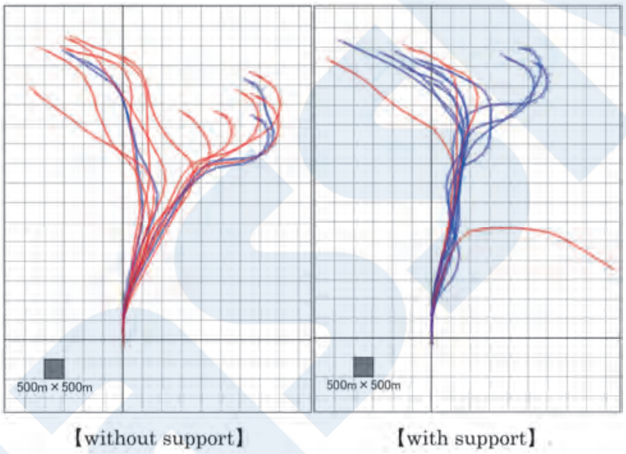


Figure 38 Track charts showing ship handling results

In this verification, 11 collisions occurred during 15 rounds of the test "Without support," but in the test "With support," the number of collisions decreased to 4. This is attributed to the fact that the support displays allowed the master / navigation officer to notice other ships with a high collision risk at the proper time and easily determine an appropriate collision avoidance action by visually recognizing waters with a high collision risk. This can be interpreted as suggesting that the result of complementing the differences in the individual situational awareness abilities and experience of the subjects is expressed in the convergence of the ship tracks.

It may also be noted that the results of an experiment under the same scenario in FY 2019, in which the subjects were license holders (professional captains and navigation officers), also showed better convergence of the tracks in the test "With support" than in the test "Without support," and the number of collisions was reduced to only 0 or 1 in the test "With support."

4.2.2 Evaluation and Analysis Using Auto Grading System

Table 7 shows the results of the comparative verification using the AGS ship handling evaluation program. The comparison was conducted for tests "Without support" and "With support." The results are shown by the colored arrows in the table. Although collisions occurred in the experiment, as described above, the score is not reduced for the respective items in AGS, but the fact that collisions occurred is shown together with evaluation for the other items. For this reason, results containing a collision were excluded from the score-based comparison. Entry into the oncoming lane (reverse travel) also occurred in some cases. For entry into a NGA, points are deducted to some extent in this case. However, in this experimental method, entry into the oncoming lane results in an extreme decrease in encounters with other ships, which would affect the scoring of the passage of the other ships. Therefore, as with collisions, results containing reverse travel were excluded from the score-based comparison.

Table 7 Evaluation of results of ship handling by auto grading system

Subject (cadet)	Result of evaluation by AGS		
	Without support (radar only)	With support (collision risk display)	Comparison
A	Collision	-109.29	↑
B	Collision	-111.84	↑
C	Collision	Collision	→
D	Collision	-129.83	↑
E	-107.43	-66.43	↑
F	Reverse travel	Collision	→
G	Collision	-63.96	↑
H	-67.07	-84.22	↓
I	Collision	Reverse travel	→
J	-119.10	-61.83	↑
K	Collision	-51.13	↑
L	Collision	-55.30	↑
M	Collision	-113.89	↑
N	Collision	-29.21	↑
O	-146.11	Reverse travel	↓
Average (*)	-109.9	-87.7	↑

<Legend>

↑ In comparison to the test “Without support,” the score increased or no collision/reverse travel occurred in the test “With support.”

↓ In comparison to the test “Without support,” the score decreased or collision/reverse travel occurred in the test “With support.”

→ Collision/reverse travel occurred in both the test “Without support” and the test “With support.”

* The average score is the value obtained by dividing the total score calculated without collision/reverse travel by the number of subjects.

Based on Table 7, the results of an evaluation of 10 of the 15 subjects showed that more appropriate shiphandling” was generally performed in the test “With support” than in the test “Without support.” From the above-mentioned track charts, it is clear that the number of collision decreased in the test “With support,” and the average score calculated using the auto grading system was also higher in the test “With support” than “Without support.” Thus, a certain ship operation improvement effect was observed with the use of the ship operation support device.

4.3 Discussion

Based on the findings of this study, the effects of the collision risk indexes and area display and the importance of education in utilizing this ship operation support device are summarized as follows.

4.3.1 Effects of Collision Risk Indexes/Area Display

The results of the simulator-based experiment and verification proved that issuance of warnings based on a collision risk index enables early discovery of collision risks by the master / navigation officer, and visualization of the basis for judging that a situation is dangerous as an area display contributes to levelling the variations in the skills of individual masters /

navigation officers, reduced collision risk and improved safety. In particular, it is suggested that the indexes/area display are highly effective in transverse passing situations, as shown in the scenarios examined in this section. In cases where a ship passes transversely across a line of multiple ships with different speeds travelling in succession, for example, when passing a sea lane, the master / navigation officer must predict the movement of each ship and the arrangement of the group of ships in the future, i.e., the future relative relationship of the ships, and then analyze and decide the route that the own ship should take. It can be said that the device described here facilitates this task. This was clearly demonstrated by the fact that a large number of collisions occurred in the test “Without support,” while the number of collisions was reduced to nearly zero in the test “With support.”

The following secondary effects can also be expected as a result of reducing the workload on the ship’s crew.

- Reduction of judgment errors by alleviating psychological stress.
- Reduction of judgment errors by allowing more time for thinking.
- Reduction of cases of overlooking important targets by observing the surroundings more calmly.
- Improvement of judgment in situations where visual confirmation is difficult, for example, at night or under low visibility conditions.

Future tasks will include preparation for system implementation in order to ensure system operation oriented toward the safety and security of the master / navigation officer by adjusting the ship operation support device for various users and ship operation environments and constructing a man-machine interface with high usability, while also focusing on the above-mentioned secondary effects.

4.3.2 Education for Utilizing Ship Operation Support Device

The effects of the collision risk display described in the preceding section are clear. However, the possibility that use of a new ship operation support device may compromise safety, depending on how well the user understands the device, was pointed out as a problem in the experiments conducted to date. Education was recently given to mates and cadets, and as a result, several perspectives were obtained, as summarized below.

- Deepening the understanding of the ship operation support device by education can contribute to the improvement of safety.
- Even if the same education is provided, the degree of understanding will vary depending the person. Therefore, it is essential to give education and training according to the levels of individuals, for example by specifically clarifying matters that seem to be inadequately understood, through workshops or the like, and providing additional individual education.
- Effective use of the ship operation support device requires knowledge/experience in ship operation practices, which are prerequisites for effectively using the device. Therefore, operation, including education and training, should be studied after clarifying the knowledge and skills required in master / navigation officers.

From the above, assuming the target of education is masters / navigation officers with varied levels of experience and skill, education for masters / navigation officers is considered to be an essential requirement. The future aims are proving the necessity of these forms of education by providing more convincing data, and establishing educational requirements for safe operation of the device.

5. SUMMARY

5.1 Results of Study

Concerning the collision risk indexes developed in this study, the companies concerned established collision risk notification algorithms based on the data from tests conducted with active ocean-going captains and navigation officers and developed prototype systems. Using a combination of the collision risk indexes and the collision risk area display, the master / navigation officer can be made aware of risk by issuing collision risk indexes, and can recognize ships with a risk of collision at an earlier timing than with the conventional visual and radar-based ship operation and select a safe course quickly, based on information concerning waters with a high collision risk provided by the collision area display. In the ship handling experiment using a ship handling simulator conducted with experienced masters / navigation officers, the number of collision accidents was significantly reduced when the prototype device was used in comparison with operation without the device, and when students with little experience in ship handling used the device, a sufficient effect was observed after education on the use of the device.

However, some masters / navigation officers failed to fully understand the functions of this device or to make full use of it. Although the number of such cases was small, as a future task, it will be necessary to study education to ensure full use of the collision avoidance support device.

5.2 Future Efforts

The navigation device manufacturers have completed prototypes of the functions and devices developed in this study. In the future, each company will pursue improvement and verification with the aim of commercializing the developed functions and devices.

The aim of the manufacturers is to achieve commercialization by around 2025 after conducting repeated verifications, bearing in mind the need to obtain approval for the devices from ship classification societies and other authorities. After the verifications are conducted, the marine transportation industry should work to substantially reduce collision accidents, prevent environmental destruction caused by accidents and improve customer services by installing the developed functions and devices on ships. In addition, Japan Marine Science intends to develop a more advanced version of the auto grading index developed in this study in order to evaluate autonomous ship operation systems that will become available in the future, and to pursue proposals to concerned parties inside and outside of Japan concerning evaluation methods for autonomous ship operation systems, which are expected to be standardized in the future.

6. CONCLUSION

As described in this paper, the contribution of the collision risk judgment method developed in this study to improving safety by levelling variations in the skills of individual masters/ navigation officers and reducing collision risk has been amply demonstrated. In the final fiscal year of the study, an experiment was conducted with candidates for navigation officer who had not yet received licenses, and it was found that the system is also effective in improving the safety of ship operation by relative inexperienced navigation officers to a certain extent, proving that the system can be adapted to various users.

In the future, this effort will proceed from the research and development stage to the implementation and practical use stage. The research findings from this study can be used not only for safety improvement through ship handling support for masters/ navigation officers of existing ships, but also as a basic technology for the situation assessment function in the automated operation ships which are currently under development.

Furthermore, this research and development project has also helped to revitalize the maritime industry, as the participants grappled with problem-solving suited to current conditions in order to prevent collision accidents by combining the knowledge of manufacturers and front-line personnel through joint efforts by navigational device manufacturers and the marine transportation industry, and businesses in the same industry worked jointly on the development with an awareness of the appropriate regions for cooperation and competition.

Currently, the members of this study team are participating in a “Demonstration project for ships using a ship operation support function and remote ship operation, *etc*.” conducted by Japan’s Ministry of Land, Infrastructure, Transport and Tourism, and a DFFAS project in a “Joint program for technological development related to a demonstration experiment of an unmanned operating ship” (MEGURI 2040) of the Nippon Foundation, in order to achieve safe navigation, including reduction of collision accidents, and improve the working environment for crew.

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ABBREVIATIONS

ICT: Information and Communication Technology
IoT: Internet of Things
CPA: Closest Point of Approach
DCPA: Distance of CPA
TCPA: Time to CPA
ARPA: Automatic Radar Plotting Aid
PAD: Predicted Area of Danger
DAC: Dangerous Area of Collision
OZT: Obstacle Zone by Target
AIS: Automatic Identification System
IMO: International Maritime Organization
ECDIS: Electronic Chart Display and Information System
ECS: Electronic Chart System
SJ: Subjective Judgment
AGS: Auto Grading System
NGA: No Go Area

Development of AI-based Automatic Collision Avoidance System and Evaluation by Actual Ship Experiment

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1. INTRODUCTION

Accompanying the growth of the global economy, the volume of maritime transport is constantly increasing, and improvement of navigational safety in overcrowded ports and congested sea areas has become a major challenge for marine transportation. Because many ship collisions are caused by human factors, it is essentially difficult to completely prevent collisions at sea as long as navigation is performed by human crews. As an additional problem, since Japan is rapidly becoming a "super-aged society," it is likely to become difficult to secure a stable supply of seafarers for domestic shipping in the near future. Considering the difficulty of a fundamental solution to the problems of collisions caused by human factors and shortages of seafarers, technological innovation through cooperation among industry, government agencies and academia are indispensable.

To address this situation, in the Maritime Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), a study was carried out in the Maritime Innovation Subcommittee of the Marine Subcommittee, Council for Transport Policy, and a draft roadmap was drawn up targeting practical application of maritime autonomous surface ships (MASS) by 2025. Development and demonstration of technologies for MASS utilizing artificial intelligence (AI) technology, etc. is scheduled for the period from 2020 to 2025. In fact, accelerated moves in the development of automatic navigation systems, not limited to "cognition" assistance in manoeuvring, but also extending to "judgment" and "action" are considered likely in the future, as seen in the development of the Nippon Foundation's Unmanned Ship Project MEGURI 2040, which began in 2020.

Self-driving technologies are being developed for automobiles preconditioned on the existence roadways and other infrastructure. However, the traffic flows of ships at sea are considerably more complex than automotive traffic because ships can basically sail anywhere, and large and small ships with different speeds and manoeuvring performance may coexist in the same waters, and unlike air traffic control systems, ships are not given instructions concerning the ship's route and speed or separation from other ships in marine traffic control. Thus, the key to realizing an automatic navigation technology is how the individual ships themselves can judge the risk of collision foreseeing future conditions and carry out appropriate evasive manoeuvring to avoid collisions, that is, collision avoidance. In order to be a successful means of transportation in the face of global competition, MASS vessels must not only avoid collisions with other ships and obstacles, but must also arrive at their destinations efficiently. Although mere extensions of existing technology do not offer an easy solution to this difficult problem, AI has great latent potential, as AI technologies continue to display capabilities that could surpass those of human beings in various fields.

The purposes of this research are to develop AI for automatic collision avoidance which will be a key technology to a navigation support system for domestic vessels and to conduct a verification experiment in congested waters using an actual ship, with the aim of realizing an automatic navigation technology, which is indispensable for realizing MASS. The individual challenges and implementation items for achieving these purposes were set as shown below. The following chapters present detailed descriptions of each of these items.

(1) Development of automatic collision avoidance AI
(2) Development of AI-based automatic collision avoidance system for use in actual ship experiment
(3) Risk evaluation of AI-based automatic collision avoidance system
(4) Evaluation of automatic collision avoidance AI by simulator experiment
(5) Evaluation of AI-based automatic collision avoidance system by actual ship experiment

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2. DEVELOPMENT OF AUTOMATIC COLLISION AVOIDANCE AI

Describing the process of collision risk judgment and selection of evasive actions in congested waters in clear, universal terms is not an easy task. In particular, virtually no teaching data are available for learning correct and erroneous manoeuvring techniques under a condition of an impending collision. Machine learning is an effective technique from this viewpoint because the machine itself is made to perform evaluations and tuning, and reinforcement learning is especially suitable in action selection problems in which the target of “collision avoidance” is clearly given. In reinforcement learning, intelligence is reinforced by repeating a process of speculative search and evaluation. Although the agent in reinforcement learning learns an action policy that maximizes the expected value of cumulative future rewards, Q-learning is one type of reinforcement learning, in which the agent learns the value of actions based on the results of actually performing those actions. While Q-learning itself is not new, highly accurate estimation of the value of actions that change complexly with respect to states is now possible by approximating the action value function Q by deep learning, and realizing the selection of the optimum action from which the largest cumulative reward can be expected. The learning technique which combines reinforcement learning and deep learning is called “deep reinforcement learning”. DeepMind applied deep Q-learning [1)] (also called “deep Q-network”) to Atari games and attracted immediate attention by enabling operation that exceeded the scores of human players. The AI technology for automatic collision avoidance developed in the present research is a further development of the results of research [2)] on automatic collision avoidance of multiple ships applying deep Q-learning.

Collision risk judgments are made by using a ship “bumper” [3)], which is the exclusion zone around a ship. Although different bumper model sizes have been proposed corresponding to the degree of congestion of the waters, in this research, we introduced a “double bumper” combining an inner bumper for congested waters and an outer bumper for open seas. The optimum action for avoiding collisions can be learned by setting a negative reward for intrusion of another ship into the bumper. As the neural network input, information concerning the ship itself, the bumper area, information on other nearby ships, etc. is given in grayscale imagery. Since learning is performed on a simulation base, a manoeuvring motion model for steering is necessary. Here, a first-order KT model was used so that learning is possible provided that the results of the zig-zag test in a sea trial are available. If deep reinforcement learning is applied to manoeuvring for berthing and unberthing, it appears to be necessary to construct a manoeuvring motion model for low speed region based on captive model tests or CFDs (Computational Fluid Dynamics). However, modelling with this degree of precision is not necessary for collision avoidance problems.

When a certain condition has been given in deep Q-learning, a NN which estimates the cumulative reward over the future in case selectable actions are taken is constructed through a very large number of collision avoidance simulations. The available actions in this research are three types, sailing straight, turning to port or turning to starboard, to enable the human evaluation of the judgments by AI in the actual ship experiment. An automatic collision avoidance manoeuvring system that can perform navigation to the destination and collision judgment and danger avoidance without human involvement is realized by combining a general-purpose autopilot and AI that avoids entry of other ships into the bumper of the own ships or drives other ships out of the own ship bumper, which is obtained as a result of deep Q-learning. The actual degree of collision risk changes dynamically depending on the relative relationship with other ships. However, in the present condition, in which there are no precedents for automatic collision avoidance by AI, risk evaluation based on only static elements was adopted, and the highest priority was given to enabling real-time evaluation of the quality of AI manoeuvring by personnel onboard the ship. Moreover, it is also necessary to perform collision avoidance well in advance so as not to threaten other ships. Therefore, although the ship used in the verification experiment was the “Fukae Maru” (training ship of the Graduate School of Maritime Sciences, Kobe University), the value of the largest ship which might possibly be encountered in Osaka Bay was used as the ship length for determining the bumper size in the AI. This data was obtained through an analysis of ship Automatic Identification System (AIS) data for 1 year.

3. DEVELOPMENT OF AI-BASED AUTOMATIC COLLISION AVOIDANCE SYSTEM FOR USE IN ACTUAL SHIP EXPERIMENT

The Kobe University training ship “Fukae Maru” is used in the automatic collision avoidance experiments in actual waters. In addition to broadcasting GPS, gyrocompass, GPS compass, AIS, radar, etc. data in an on-board LAN, the ship is already equipped with an autopilot system [4)] utilizing external signals. In implementation of the AI-based automatic collision avoidance system, a sub-PC and a main PC were installed. The sub-PC receives and decodes sensor information, performs databasing, generates information by time difference and monitors received and transmitted signals, while the main PC contains the AI program, which outputs the optimum action based on input data on an arbitrary number of other ships and obstacles in order from the nearest ship to the own ship from the database. Figure 1 shows a block diagram of the system configuration. Although AIS and radar TT data are used in detection of other ships and obstacles, this system does not require collation and matching of information such as the ship position and speed vector, which are obtained from multiple sensors. In the automatic collision avoidance system implemented in this project, UDP communication via the on-board LAN is performed between the PCs and the existing autopilot, and autopilot sails the ship on the optimum course instructed by the AI.

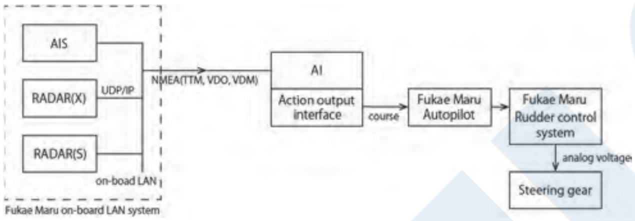

Figure 1　Block diagram of AI-based automatic collision avoidance system

Switching to the automatic collision avoidance mode and setting of way points are performed via the user interface in Fig. 2. The screen displays the own ship, other ships and obstacles, the bumper zone, the target course, etc. The specifications and layout were decided with the cooperation of licensed mariners to enable operability comparable to that of radar and inputting with the minimum mouse operation. Because the NN is a nonlinear statistical filter, it is difficult to display the relationship between inputs and outputs to human operators. Therefore, the interface makes it possible to distinguish whether the course instructions provided by AI at each time-step are the normal sailing mode or the collision avoidance mode. Because the double bumper is always displayed on the screen, the quality of AI-based collision avoidance manoeuvring can be judged easily by on-board personnel, based on whether other ships or obstacles will enter the bumper zone or not.

Switching from normal operation to AI manoeuvring in the actual ship experiment is performed by switching from hand control to remote control by a rotary switch based on the judgment of ship's captain. Automatic collision avoidance by AI is started by pushing the transmission button from the interface on the main PC, and if the captain judges that a dangerous condition exists, it is possible to return immediately to hand control simply by switching the same rotary switch.

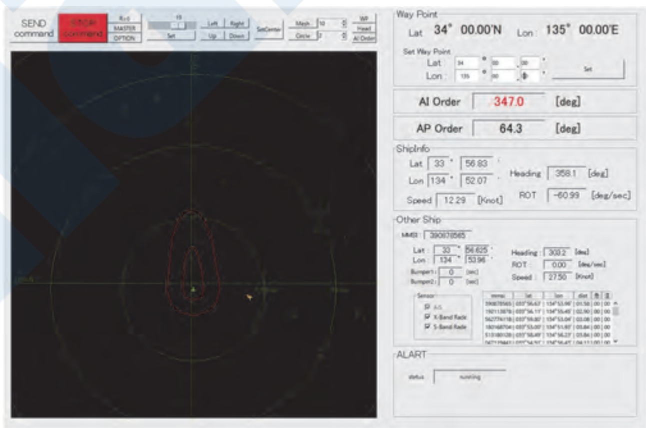

Figure 2　User interface of AI-based automatic collision avoidance system

4.　RISK EVALUATION OF AI-BASED AUTOMATIC COLLISION AVOIDANCE SYSTEM

4.1　Overview of FMEA

In this research, Failure Mode and Effects Analysis (FMEA) was adopted as a method for risk evaluation. The target of FMEA is the demonstration equipment of the AI-based automatic collision avoidance system. The purpose of this analysis is to clarify whether the functions required in the system can be achieved inconceivable failure modes or operation becomes unsafe and whether alternative measures have been taken in case operation becomes unsafe, and to verify logically whether deficiencies have not been included in the system configuration and design in advance.

Figure 3 shows the configuration of the on-board system of the Fukae Maru. Information on the own ship and its surroundings collected by AI-PC2 (sub-PC) is transmitted to AI-PC1 (main PC), and AI-PC1 outputs the optimum heading based on that information. Autopilot controls the ship’s rudder according to the heading order from AI-PC1. Since the target system of the FMEA is limited to only the demonstration equipment of the AI-based automatic collision avoidance, functions used in normal operation are excluded from the FMEA. Accordingly, the target of the FMEA is the newly added equipment and the equipment that have information communication between AI-PC1 and PC2.

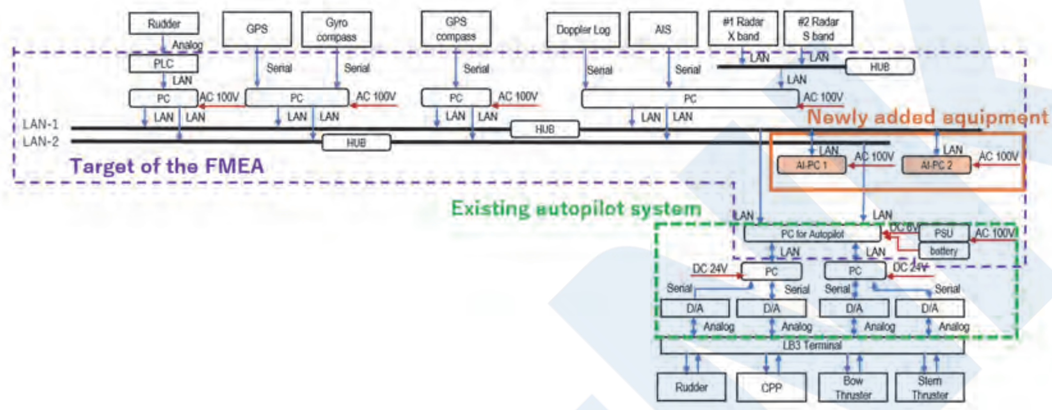

Figure 3　Configuration of on-board system

This FMEA is focused on AI control ON mode because, in the case of AI control OFF mode, the system is regarded as a normal operation by disconnecting the communication line between the current system and the AI system. However, the failures that affect normal operation are in the scope of this analysis. The top failure events are as described below.

- Equipment failure
- Loss of signal

The FMEA for equipment failure and loss of signal is designed to be expressed in one sheet. The FMEA was conducted referring to the “Guidelines for Implementation of Failure Mode and Effects Analysis (FMEA)” issued by ClassNK.

4.2　FMEA Test Using Actual System

In the demonstration experiment using a ship, safe navigation and operation are the most important. Therefore, the on-board testing is focused on how to acknowledge the system failure by operators and how to switch the system mode to AI control off based on the FMEA sheet.

In the FMEA, although various failure modes such as power supply failure, component failure, communication failure, wiring failure, and sensor failure are set, the effects of various failures of surrounding devices on AI-PC1 and AI-PC2 can be regarded as communication failures that disrupt signals from the devices concerned. Therefore, the targets of this test are power source anomalies of AI-PC1, AI-PC2, LAN1 HUB, and LAN2 HUB, which are the main communication paths, and communication failures of the two AI-PCs, which are the core elements of the system.

The test results confirmed that this is a design in which the system operator can recognize failures, for example, by notification of the system operator when an abnormality occurs in the equipment. It may be noted that multiple FMEA tests were conducted before reaching this result, and the fact that this testing process can contribute to the implementation of effective measures for design deficiencies and safe test voyages is considered to be one of the benefits of conducting the FMEA.

5.　EVALUATION OF AUTOMATIC COLLISION AVOIDANCE AI BY SIMULATOR EXPERIMENT

Before conducting an actual ship experiment using the AI-based automatic collision avoidance system, verification and evaluation by simulator experiments are indispensable. In this research, preliminary safety verifications were carried out by two approaches, namely, quantitative evaluation using a ship handling evaluation tool and qualitative evaluation by licensed mariners using a simulator.

5.1 Quantitative Evaluation Using Ship Handling Evaluation Tool

5.1.1 Ship Handling Evaluation Tool

The main elements for recognition of the risk of collision with another ship by the ship's operator are the relative distance between the two ships, the rate of change in bearing, whether the encounter involves bow crossing or stern crossing, etc. As an index for evaluating the results of collision avoidance manoeuvres, Japan Marine Science Inc. has proposed an evaluation area diagram for risk evaluations in which "Danger," "Caution" and "Safety" areas are defined by using the relative distance between ships and the rate of change in bearing [5]. In this evaluation region diagram, the positional relationship (i.e., the "encounter situation") with other ships and the relationship between the relative distance and relative bearing change rate with other ships are classified into multiple graphs, on which "Caution" and "Danger" areas are set. However, in collision avoidance by the developed automatic collision avoidance AI, collision risk is assessed by using a new evaluation area diagram [6] in which the crossing relationship is classified into ships crossing from starboard and ships crossing from port side from the viewpoint that becoming the "stand-on vessel," as specified in the Act on Preventing Collision at Sea, should be avoided as far as possible.

A point deduction system was proposed for evaluations of manoeuvring results, in which a weighting coefficient of −2 is calculated when the ship enters a "Danger" area, and −1 and 0 are calculated for the "Caution" and "Safety" areas, respectively. Table 1 shows the evaluation formulas and the evaluation areas used in preparing the area diagram.

Table 1 Evaluation formulas and definitions of evaluation areas in preparation of area diagram.

Encounter situation		*Evaluation formula*		*Evaluation*
Head-on/ Crossing from Starboard	Bow Crossing	$\theta < \infty$	$R < 185.2\,[m]$	Danger
		$\theta \leq 4.5 \times 10^5 \cdot R^{-1.7}$	$R < 1852.0\,[m]$	
		$\theta < \infty$	$R < 463.0[m]$	Caution
		$\theta \leq 15.0 \times 10^5 \cdot R^{-1.7}$	$R < 3{,}426.2[m]$	
		Range excluding danger area and caution area		Safety
	Stern Crossing	-		Danger
		$\theta \leq -5.2 \times 10^5 \cdot 170^{-1.7}$	$R < 185.2\,[m]$	Caution
		$\theta \leq 15.0 \times 10^5 \cdot R^{-1.7}$	$R < 3{,}333.6\,[m]$	
		Range excluding caution area		Safety
Same-way		$\theta < \infty$	$R < 277.8[m]$	Danger
		$\theta < \infty$	$R < 463.0[m]$	Caution
		$\theta \leq 15.0 \times 10^5 \cdot R^{-1.7}$	$R < 926.0\,[m]$	
		Range excluding caution area		Safety
Crossing from Port	Bow Crossing	$\theta < \infty$	$R < 185.2[m]$	Danger
		$\theta \leq 4.5 \times 10^5 \cdot R^{-1.7}$	$R < 1852.0[m]$	
		$\theta < \infty$	$R < 463.0[m]$	Caution
		$\theta \leq 15.0 \times 10^5 \cdot R^{-1.7}$	$R < 14{,}816.0\,[m]$	
		Range excluding danger area and caution area		Safety
	Stern Crossing	$\theta \leq -5.2 \times 10^5 \cdot 170^{-1.7}$	$R < 185.2[m]$	Caution
		$\theta \leq -5.2 \times 10^5 \cdot R^{-1.7}$	$R < 9{,}260.0[m]$	
		Range excluding danger area and caution area		Safety
θ : Rate of change in bearing *(deg./min.)*		R: Relative distance *(m)*		
Danger		: Unacceptable area		
Caution		: The area where own ship commences to avoid or expect another ship to avoid		
Safety		: Acceptable area		

The area charts were formulated based on approximately 30,000 datapoints in a manoeuvring experiment in which the subjects were the captains and pilots of ocean-going ships [5]. In addition, because the results of a collision avoidance demonstration experiment with a coastal tanker showed the validity of an evaluation area diagram assuming congested waters for a ship with a total length of 50 m or more, this was adopted as a technique for objectively evaluating the results of the automatic collision avoidance by AI in this research.

5.1.2 Evaluation Results of Collision Avoidance Manoeuvring

Using the ship handling evaluation tool described in the previous section, collision avoidance manoeuvring by AI was scored for a total of 39 scenarios simulating traffic flows in actual waters, including typical 1:1 encounter scenarios and scenarios involving encounters with multiple other ships. Examples of the test scenarios and evaluation results are shown in Figs. 4 and 5, and Table 2, respectively. In the top part of Fig. 5, the graph in the upper left is the area diagram for bow crossing by a ship crossing from starboard, that at the lower left is for stern crossing, and that in the upper right is for a same-way ship. Here, the results of manoeuvring in the encounter situation in Fig. 4 are plotted as red dots at 10 sec. intervals based on the relationship between the relative distance and relative bearing change rate with respect to the other ship. The lower part of Fig. 5 is an evaluation area diagram for a ship crossing from port, but in this scenario, there is no ship that fits this description. Table 2 shows the results of scoring of the test scenario in Fig. 4 using the evaluation tool. The fact that the own ship passed a ship crossing from starboard, which crossed in front of the own ship, without entering the Caution or Danger areas, can be read from both the area diagram and the scores.

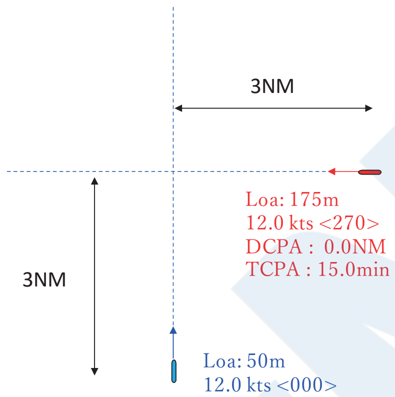

Figure 4　Example of test scenario (1:1 crossing ship)

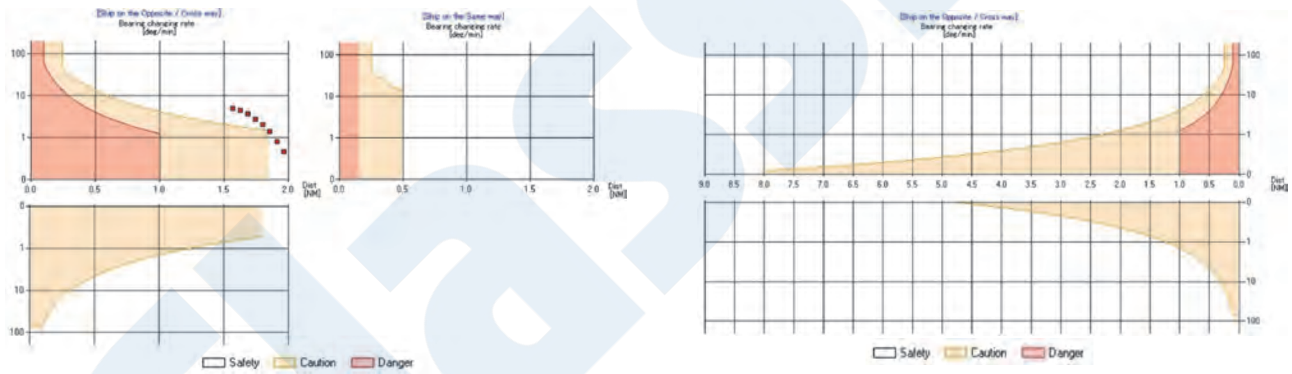

Figure 5　Example of evaluation areas

Table 2　Example of collision avoidance manoeuvring evaluation results

	Safety	Caution	Danger	Total
Sum Counts	917	0	0	917 (a)
Weight Factor	0	-1	-2	-
Sum Score	0	0	0	0 (b)
Total Score	-	-	-	b/a x 100＝0

Thus, the results of scoring all of the scenarios confirmed that the ship essentially did not enter the “Danger” area and the frequency of entry into the “Caution” area was also kept within the allowable range, according to licensed mariners (as described in the next section), under the condition that deceleration was not allowed. Here, it should be noted that collision avoidance is difficult under these scenarios without changing speed. Further improvement of manoeuvring actions is expected by improvement of the bumper zone and inclusion of speed changes, which are not considered at present in the reinforcement learning.

5.2 Qualitative Evaluation by Licensed Mariners

The persons who participated in the evaluation were 5 licensed mariners (4 captains and 1 first officer) with extensive experience in manoeuvring large ships. The manoeuvring evaluation was conducted by requesting feedback from each subject after observing automatic collision avoidance manoeuvring on a simulator. Under each scenario, the subjects checked the encounter situation from the viewpoint of the own ship, and also checked the encounter situation using arbitrary other ships (large ships), and reported that they had no feelings of unease regarding the movement of the own ship from the viewpoint that "the own ship's movements should not cause anxiety on the other ship, which was being maneuverer by a human operator."

Because the captain of a ship has the authority to make final decisions regarding manoeuvring when conducting the actual ship experiment with the "Fukae Maru," automatic collision avoidance by AI was reproduced on the ship handling simulator and an evaluation was conducted with the cooperation of the crew of the "Fukae Maru", from the viewpoints of the timing of initiation of collision avoidance manoeuvring, the method of collision avoidance and avoidance angle, and timing of return to the original course, etc. with the crew members acting as the evaluators.

In the results of the verification by these evaluators, overall, there was no feeling of discomfort concerning the ship's movement during automatic manoeuvring. However, duly considering the fact that this was for an actual ship experiment in congested waters, problems were identified, as shown in Table 3, and the response measures deemed necessary in an actual ship experiment were taken for each. The actual ship experiment was then carried out after confirming that all of these problems had been solved.

Table 3 Problems of automatic collision avoidance AI in actual ship experiment and response measures

Problem	Solution
Risk of turning to port contrary to COLREGs in case of ships crossing from starboard.	The learning environment was improved, and adjustments were made so that actions apply the COLREGs.
Unsteadiness (wandering) of the bow can be seen (due to turning the rudder to the right, followed by turning back to the left).	The method of giving rewards and algorithm of connection with the autopilot were reviewed to reduce wandering.
Intentions of AI in collision avoidance manoeuvring are unclear.	An interface that shows the bumper and other ships was prepared so that the ship's operator can predict the AI manoeuvring actions.
Experiment may be difficult depending on the environment, such as congestion of surrounding waters, weather, sea conditions, etc.	The environmental conditions were clearly specified in the test proposal.

There was also feedback that it may be necessary to reduce speed by using the engine in some manoeuvring situations, rather than manoeuvring to avoid collision by using the rudder. However, this speed reduction option was not provided in this actual ship test. Therefore, it was decided that safety should be ensured by human fallback if the ship encounters situations where speed reduction is necessary.

6. EVALUATION OF AI-BASED AUTOMATIC COLLISION AVOIDANCE SYSTEM BY ACTUAL SHIP EXPERIMENT

A demonstration experiment using the AI-based automatic collision avoidance system was conducted in the congested waters of Osaka Bay over a 3-day period from December 8 to 10, 2020. The waters where the experiment was conducted were southward from Kobe Bay and northward from the Sumoto offing lighted buoy. The safety criteria for conducting the demonstration test of AI manoeuvring were specified as follows:

- Wind speed not exceeding 10 m/s, wave height not exceeding 2 m and visibility of at least 2 miles.
- No abnormalities of the nautical instrument or machinery of the ship itself, or of the functions of AI manoeuvring.
- Judgment by the captain or the mariner on watch duty that congestion and other conditions are suitable for the test.

Figure 6 shows the system for implementation of the actual ship experiment. To ensure safety, the normal watch condition of the ship was maintained, uninterrupted monitoring was conducted by the general supervisor of the test and the engineer responsible for the AI manoeuvring functions, and preparations were made for unexpected events.

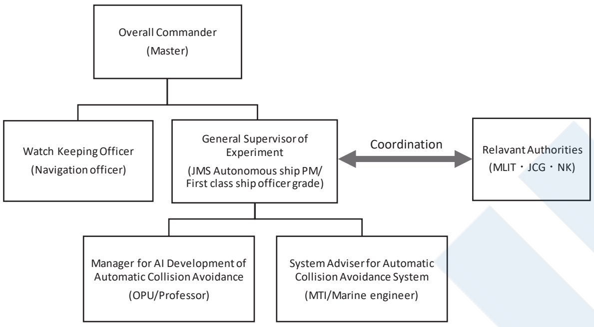

Figure 6　System for implementation of actual ship test

In the actual ship experiment, automatic collision avoidance by AI was conducted for more than 21 encounter situations over the 3-day period. During the experiment, manual manoeuvring was performed so as to create a variety of encounter situations in which a risk of collision would occur. After inputting the latitude and longitude of the way points into the AI-based automatic collision avoidance system, the manual operation was switched to the AI operation mode, and a series of ship manoeuvre until return to the original course was confirmed. Figure 7 shows a photograph of the training ship “Fukae Maru” used in this experiment, Fig. 8 shows an encountering condition during automatic collision avoidance and Fig. 9 shows a photograph of inside the bridge during the experiment.

Figure 7　Training ship “Fukae Maru” used in the verification experiment

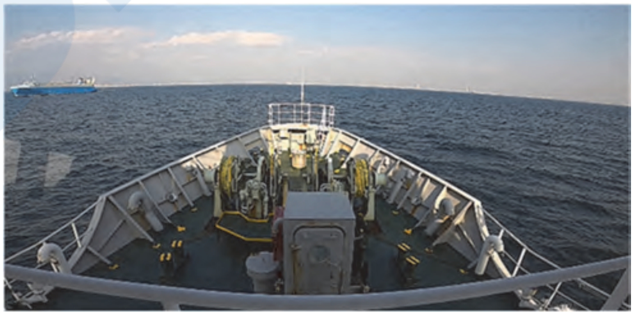

Figure 8　AI-based automatic collision avoidance in Osaka Bay

Figure 9　Condition of inside the bridge during the actual ship experiment

In evaluation of AI-based automatic collision avoidance system, the ship sailed toward the set way points under autopilot, and when the risk of a collision appeared, the capability to properly avoid the collision under the bearing instructions by AI was confirmed. Examples of the experimental results are shown in Figs. 10 and 11. As shown in Fig. 10, in case automatic collision avoidance is initiated from a condition in which another ship is outside the bumper, collision avoidance manoeuvring was performed so that the other ship would not enter the outer “open-water” bumper. The results showed that the ship returned to the original course after the risk of collision with a vessel on an opposite course disappeared. Figure 11 shows a case of initiating automatic collision avoidance from a condition in which other ships are already present inside the bumper. Here, it was confirmed that collision avoidance manoeuvring was carried out so that the other ships did not enter the inner “congested” bumper. The results of this experiment suggested that appropriate collision avoidance manoeuvring corresponding to the degree of congestion is realized by introducing the double bumper, which gives different negative rewards depending on the degree of collision risk.

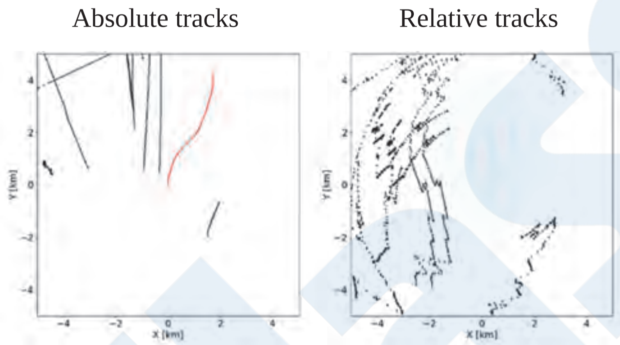

Figure 10　Result of automatic collision avoidance by AI (initiated from condition in which other ships are not present in the bumper)

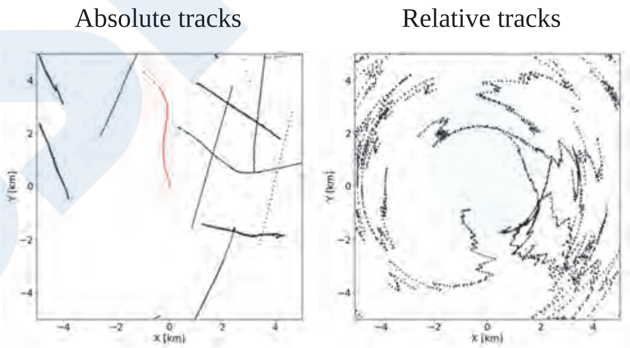

Figure 11　Result of automatic collision avoidance by AI (initiated from condition in which other ships are present in the bumper)

Although this test was conducted in congested waters, where operating fishing boats and buoys are present in addition to general merchant ships, the results confirmed that the ship avoided collisions with other vessels at an appropriate timing under the automatic course control by AI and returned to the original course when the surrounding conditions allowed. In this actual ship experiment, there were time lags of the sensor information till reached to AI and time delay until the rudder was actually operated in response to the course instructions by AI. In addition, there were natural external disturbances, sensor errors and irregularly and frequently changes in the heading exist which do not exist in the simulation. Overall, however, it can be said that the fact that the collision avoidance results obtained in the actual ship test were similar to those in the preliminary verification using the ship handling simulator was an important result.

7.　CONCLUSIONS

An automatic collision avoidance system combining an ordinary autopilot and collision avoidance AI based on deep reinforcement learning was developed, and after evaluation using a ship handling simulator, an actual ship test was carried out in Osaka Bay. As a result, an automatic collision avoidance test in congested waters by the course instructions by AI was conducted successfully for the first time. Because manoeuvring results similar to those of the preliminary ship handling simulator experiment were also obtained in the actual ship experiment, it will be possible to proceed with improvement and evaluation of the AI in the future centring mainly on simulation and simulator experiments. On the other hand, for full-scale practical application, it is desirable to strengthen the visualization of AI's manoeuvring instructions, ensure that crew members can understand the intentions of the AI and develop a man-machine interface for approving those intentions. In this research, we used a fixed bumper model in which the degree of collision risk does not change with an encounter situation. However, in actual situations, the risk of collision changes in time. Thanks to the result of successful completion of the automatic collision avoidance experiment using an actual ship, development and introduction of AI that returns an output close to that judged by veteran captains corresponding to dynamically changing collision risk can be expected in the future.

Using the amount of knowledge and experience gained through this actual ship experiment, we will try to realize practical application of an automatic navigation technology at an early date, and contribute to labour-saving and improved safety in coastal navigation by preventing maritime accidents caused by human factors and improving the working environment for seafarers. We hope the success of this actual ship experiment accelerates research and development of marine autonomous surface ships (MASS) in the future.

ACKNOWLEDGMENT

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Challenge of Technology Development through MEGURI 2040

— For Safe Navigation and Workload Reduction —

Takeru SUZUKI*

1. INTRODUCTION

Ships, which are capable of transporting large volumes of cargos at one time, will play a key role in a modal shift as a means of transportation with low environmental impacts. Even though Japan is an island country, it has long been possible to obtain desired items anytime and anywhere in this country thanks to economic growth and globalization of the economy. International shipping companies transport raw materials and products from overseas to Japan and transport domestics goods to other countries, while coastal shipping companies in transport cargos shipped and delivered inside Japan, including those transported by international shippers. The coastal shipping industry fulfils an important function in the supply chain with other countries and is part of the infrastructure of daily life that supports domestic logistics, but has also faced labor shortages due to Japan's declining population and a special work environment different from that on land for many years. Although a reconsideration of capitalist society is now widely discussed against the backdrop of environmental destruction and the increasingly frequent and large-scale natural disasters associated with climate change, rapid changes in systems that were constructed and used over many years do not appear realistic. If this is so, it is self-evident that pork from America, salt from Mexico and iron ore from Australia will continue to be necessary, whether we aware of it or not, and the coastal shipping industry will also be a necessary presence as the infrastructure for supplying those and other goods. To provide stable supply service and promote a modal shift, it will be necessary to make efforts to improve the workplace environment by reducing the workload on seamen, and to improve navigational safety by preventing human error caused by inadequate watch duty and improper ship handling, which is also an issue.

In responding to these issues, a consortium of coastal ship companies and shipbuilders, equipment manufacturers, engineering companies and others is planning to conduct demonstration experiments of unmanned ships as part of the activities of the MEGURI 2040 Project sponsored by Nippon Foundation, which has the same sense of crisis. In this article, the author will present an overview of the MEGURI 2040 Project and examine whether its technologies offer a solution to the above-mentioned issues.

Here, the author wishes to note that his career to date has mainly involved sales and purchasing work in profit-and-loss departments, beginning with the containership department and also including start-ups of logistics projects with other companies, and he does not possess a technical background. Thus, this technical report was written from the viewpoint of the survival, business expansion and differentiation of services of shipping companies. The reader's understanding of this point is requested.

2. MEGURI 2040 PROJECT

The MEGURI 2040 Project, which is sponsored by the Nippon Foundation, was started in February 2020 with the aim of solving the problems of shortages of seamen due to an aging workforce, maritime accidents caused by human error and other challenges facing the coastal shipping industry by realizing unmanned ships. Demonstration experiments are to be conducted by the end of fiscal year 2021.

2.1 Current Status of Shortage of Seamen in Coastal Shipping

According to Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT), 28,435 seamen were employed in coastal shipping as of 2019, but the workforce is aging, as almost half of them were 50 years or older [1)]. Moreover, persons aged 60 years and older accounted for more than 35 % and can be expected to retire within a few years. On the other hand, the number of suitable young seamen is small, as the percentage of seamen under age 30 is a little less than 20 %, indicating that the shortage of seamen is becoming a chronic structural problem. These conditions have led to labor pirating, i.e., efforts to hire away coastal

* Mitsui O.S.K. Lines, Ltd.

seamen from other companies, and conditions where dozens of companies may attempt to recruit a single resigning seaman. This is also borne out by statistical results showing that 35 % of resigning seamen cite “personal reasons” as the reason for resigning after less than 1 year in a company. As a result, all companies consider securing the necessary number of seamen to be their highest priority, and efforts to ensure safe navigation have been shelved and are not contributing to reducing accidents.

Against this background, companies have improved the working environment for seamen, for example, by improving crew spaces, providing more toilets and shower rooms, installing complete Wi-Fi and introducing new navigational devices. Nevertheless, conditions have continued to deteriorate due to an absolute shortage of seamen, as seen in extended embarkation periods and increased total working hours because no replacement personnel are available. For ship owners, reducing the workload on seamen is the highest priority item. If it is possible to realize automation during voyages and ultimately, autonomous operation of ships, this is expected to lead to a reduction of workloads and a more stable shipboard life for seamen by reducing the number of watches to even one to two watches.

2.2 Causes of Accidents

The majority of accidents at sea are caused by human error in the form of poor performance of watch duties, improper steering, failure to check the ship’s position, inattention to weather and sea conditions, inadequate investigation of channels and the like [2]. What causes human error? In short, human error occurs “because we’re human,” but even a little analysis suggests various causes, such as human misapprehensions and assumptions, loss of concentration, failure to think deeply and panic in the face of unexpected situations. Countermeasures have focused crew training and various types of campaigns, that is, approaches to improve human performance, but this has not eliminated human error. Rather than saying “we’re only human” and resigning ourselves to this situation, an approach that prevents the occurrence of human error by mechanization and automation is necessary. One aim of this Project is to verify the technical aspects of those efforts.

2.3 Purposes of Participation by Mitsui O.S.K. Lines

Although crew workload reduction and safe navigation do not directly concern the shortage of seamen, they are also important issues in the international shipping industry. Mitsui O.S.K. Lines decided to participate in the MEGURI 2040 Project with the aims of continuously provide stable service and stimulating demand for maritime transportation in both international and coastal shipping by solving these problems.

3. OVERVIEW OF DEMONSTRATION EXPERIMENTS

An autonomous navigation system will be retrofitted on existing coastal ships, and an experiment consisting of unmanned operation from unberthing to berthing will be conducted. In actuality, however, these ships will carry a normal crew. Since the manning requirements for seamen are specified in the laws which are currently in force, and no special treatment is provided for responsibility in case of unmanned navigation, the person responsible for ship operation in the demonstration experiments will be the captain, and actions to interrupt or stop the experiment will be made on the captain’s judgment. The system and operation also make it possible to switch quickly from autonomous operation to ordinary manual operation during the experiment.

The Project was started in February 2020, and demonstration experiments in actual waters are planned for the second half of 2021 through early 2022 (end of FY 2022), while also developing and verifying the element technologies.

3.1 Demonstration Experiment Ships

The demonstration experiments will be conducted with ships of two different sizes and types, a large-scale car ferry called the “Sunflower Shiretoko” (owned and operated by MOL Ferry Co., Ltd.), which is a driving force in modal shift, and 749 type container ship, the “Mikage” (owned by Imoto Corporation, operated by Imoto Lines, Ltd.), which is a mainstay-size ship in coastal shipping. The demonstration experiment routes of the respective vessels will actual waters spanning 400 miles from Tomakomai Port to Oarai Port and 145 miles from Tsuruga Port to Sakai Port, respectively.

Table 1 Principal particulars and experiment routes of demonstration experiment ships

Ship name	Sunflower Shiretoko	Mikage
Type	Car ferry	Containership
Gross tonnage	11 410 t	749 t
LOA	190.0 m	95.5 m
Beam	26.4 m	13.5 m
Draft	6.85 m	3.8 m
Propellers	CPP × 2 units	CPP × 1 unit
Thrusters	BT × 2, ST × 1	BT × 1
Commercial route	Tomakomai Port ⇔ Oarai Port	Various
Demonstration experiment route	Tomakomai Port → Oarai Port (400 miles)	Tsuruga Port → Sakai Port (145 miles)

Figure 1 "Sunflower Shiretoko"

Figure 2 "Mikage"

3.2 Technology Development

Autonomous operation is realized by perception and cognition, judgment, and control (operation). Cognition means estimation of the position, course, speed and heading from the own ship of perceptual information (i.e., other ships, buoys and obstacles) obtained from various sensors, and sensor fusion which integrates that information. Judgment and control comprise the course planned by seamen, the predicted behavior of other ships in the vicinity of the own ship, creation of candidate collision avoidance paths based on nautical chart information and evaluation of those alternative paths and course and path following control.

Technology development of the perceptual and cognitive portion of demonstration experiment ships will be carried out by Furuno Electric Co., Ltd., and technology development of the judgment and control portion will be the responsibility of Mitsu E&S Shipbuilding Co., Ltd. As a mooring support technology, a technique for dropping heaving lines from the ship to the quay by using a drone (unmanned aerial vehicle: UAV) will be developed by A.L.I. Technologies.

Table 2 Outline of fields and companies responsible for developed technologies

	Perceptual & cognitive	Judgment	Operation
Developer	Furuno Electric Co., Ltd.	Mitsui E&S Shipbuilding Co., Ltd.	
Outside port	Own ship surroundings cognitive technology	Collision avoidance manoeuvring automation	
Inside port		In-port manoeuvring automation	
	Berthing/unberthing support system	Berthing/unberthing automation	
	Mooring support system (A.L. I Technologies)		

The accuracy of these respective technologies is currently being improved based on repeated feedback from the ship companies and seamen who will be the users.

3.3 Guaranteeing Safety

A risk assessment by the HAZID technique was conducted by ClassNK Consulting Service Co., Ltd. and Nippon Kaiji Kyokai (ClassNK), which were appointed for this work. The items examined for the two demonstration experiment ships consisted of ⅰ) Review of operation and new technologies of unmanned ships, ⅱ) Identification of potential hazards related to unmanned ships, ⅲ) Investigation of the effectiveness of existing safety measures by risk analysis and ⅳ) Additional risk control measures if necessary. A simple version of the manual was prepared for easy reference by seaman to enable sure feedback when hazards occur during a demonstration experiment.

For the technologies of collision avoidance automation, automation of manoeuvring when in port and automation of berthing/deberthing, the demonstration experiments with the actual ships will be carried out after verification of collision avoidance action and identification of points requiring improvement by using a 3D shiphandling simulator developed by MOL Marine & Engineering Co., Ltd. and implementation of the appropriate countermeasures.

3.4 Cooperation System

A cooperation system involving many persons is necessary in large-scale demonstration experiments using ships that are actually in commercial operation, as in this Project. Coordination of this system is a role of the shipping company.

Naturally, the consortium members explained these demonstration experiments to a large number of related parties, including the MLIT, Japan Coast Guard, the Maritime Safety Agency offices in each port, the port administrators and port controllers, fishery cooperatives, and the users of cruisers and fishing boats using the ports.

4. DIFFICULTIES CONFRONTED

Because one condition of the grant from the Nippon Foundation was demonstration experiments using existing coastal ships, that is, ships which are in commercial operation, the operating schedules of the ships were arranged, and a schedule for entry into dock for equipment installation and element experiments was drawn up. In arranging the operating schedules of the ships for the demonstration experiments, generous cooperation by the ship owners and operators, Imoto Corporation, Imoto Lines and MOL Ferry Co., was necessary in deciding to forgo current profits in order to invest in the future potential of these technologies.

In the case of the containership "Mikage," a number of engineers and related parties will be aboard the ship during the demonstration experiment. Because the number of persons onboard exceeded the ship's official capacity, it was necessary to complete temporary navigation procedures in order to temporarily increase the ship's capacity. The ship's living quarters were also upgraded and additional lifeboats and life vests were provided.

In the demonstration experiment using the 3D simulator, the desired control was not possible because the cycle of the signal output from the simulator was different from that of the automatic shiphandling module. This problem was resolved safely by modifying the device.

5. FINDINGS OF THE STUDY

Although the demonstration experiments are scheduled to be performed during the present fiscal year 2021, which is the final year of the MEGURI 2040 Project, the following describes the findings of the study up to this point.

5.1 Perspective of System

As the first finding of this study, the perspective of seamen and the perspective of the system used in the experiments are different. For example, in docking at a pier, a human agent (captain, etc.) determines the condition of the ship (ship position, approach angle, distance to quay, etc.) by observing the distance and angle between a part of the ship's structure such as the mast light and a landmark on land. In contrast, the system steers the ship by using the distance and angle from the bow, stern and bridge to the quay as various types of sensor information. The former is an intrinsic perspective, that is, a subjective perspective, whereas the latter is an extrinsic perspective using back-calculation from the purpose or system design. Human agents do not have any means of evaluating this determination of the ship's condition from a completely different perspective. Even assuming a human agent understands the meaning of the numerical values, which are different the ordinary perspective, that person does not use those values in steering the ship. Thus, it is reasonable to think that the human (mariner) cannot perform an evaluation of their validity and safety. Moreover, a cross-evaluation between different human agents is difficult because the guidelines and numerical values used as references differ depending on the captain.

5.2 Evaluation of Shiphandling Method

Since this is the case, the object of evaluation is the movements of the ship based on those sensor values. This was the second finding of the study. It is appropriate to evaluate the aimed ship position and attitude after certain minutes by turning the rudder at a certain timing and to what angle. However, there is one problem here: Because steering methods also differ depending on the captain, the evaluation standard is whether the steering method is “acceptable” or not. Although an acceptable method may also be the best method, the evaluation standard is whether it is acceptable or not. In other words, it is not possible to evaluate whether the plan and movements displayed by the system represent the optimum solution or not. Thus, there are as many solutions as there are systems, and even the same system will give different solutions when logic and parameter tuning are performed. This suggests that autonomous navigation, including these unmanned ships, will contain huma-like elements, and just as humans make mistakes, the system can even also make mistakes. In order to judge this, a human machine interface (HMI) which makes it possible to understand the plan for the future and the present situation is needed. HMI is a tool for communication between humans and the system. In addition to use it on the ship, HMI is necessary and indispensable for remote monitoring and at the same time, it is also essential for improvement of the system.

5.3 Perception and Cognition by Sensors

Now let us return to the discussion of the sensors. Various statistics show that the majority of accidents are caused by human error, and many of those accidents are caused by failure to perform watch duty or poor watch performance, for example, overlooking other ships or obstacles and erroneous judgment of their condition. Although the navigation officer keeps watch by visual observation or by monitoring navigational instruments such as radar, ECDIS, etc., depending on the waters and the degree of visibility, it often happens that veteran navigators recognize other ships and observation more reliably. While some people may call this “intuition,” it is the result of experience. That is, cognition which is capable of recognizing whether an object is a ship or not is possible as a result of accumulating experience in making total judgments of multiple information, such as the appearance of objects in clear weather, rainy weather and at night, how the object moves, how the object responds to the movements of the own ship, whether land is nearby, the water depth in the area, and so on. This is quite difficult for young navigators with limited experience.

On the other hand, computers can memorize patterns in which the appearance in a certain environment indicates a certain type of object and calculate their probability. Therefore, there is a high possibility that a computer can realize superior perception at night-time, in heavy fog and under other low-visibility environments that are difficult for humans. However, in order to achieve cognition on the same level as veteran navigators, it is considered necessary to develop an algorithm that realizes the similar logic as the perception and cognition performed by humans, including the above-mentioned function of making total judgments from multiple information, and a function for making corrections in judgments that have already been given based on information that changes with the passage of time. This is the third finding.

5.4 Investment in Sensor Technology

Then, what types and numbers of sensors should be installed on an unmanned ship? Because costs will increase depending on the number of sensors installed, there is little incentive to introduce sensors which do not have large visible effects. “Large effects” are not a characteristic of the sensor as such. It is necessary to show how the sensors contribute to safe navigation, and then how they contribute to reducing the workload of seamen by expanding the scope of discussion to include cognition, judgment and operation. Realistically, however, the number of sensors that can be added in addition to existing sensors is probably limited.

Another issue is how to estimate tidal currents and waves, since these phenomena cannot be captured by sensors. In systematizing the sensory process of human beings, estimation may be possible by developing an algorithm. Therefore, as the fourth finding, this Project revealed the necessity of system integration is performed by systemic design, in which the information to be acquired is selected and utilized in perception, judgment and operation.

5.5 Time Required from Development to Verification

The fifth finding is the large amount of time required to conduct the experiment. Unlike automobiles, the specifications of ships are different in every ship. Even assuming sister ships are built from the same design drawings, the performance of the two ships will not necessarily be the same if the shipbuilding berth is different. In explaining this difference, the auto industry spends considerable time and uses a number of prototype cars in performance and durability testing before marketing a line of mass-produced automobiles with identical performance. However, in the shipping industry, ship type development and performance evaluations inevitably rely on CFD and tank tests using ship models due to the small production volume, long time required for shipbuilding and high unit cost of the ships. That is, in the case of ships, adjustment of one cognition system, one judgment system, one operation system and the autonomous navigation system integrating those systems in each ship is invariably necessary. The fact of individual adjustment might also be the same in automobiles, but the timing and duration are different. As noted above, in automobiles, new performance is evaluated before a product is marketed. Tests are conducted under every conceivable environment, including wet pavement, environments with poor visibility, strong winds, environments with prolonged high temperatures and under high/low humidity conditions, and the model is only marketed after passing those tests. In the case of a ship, adjustments are made after construction is completed because performance and durability are evaluated using the actual ship in a substantially completed form. In addition, adjustments may become necessary when the environment changes. Unless the ship is fortunate enough to have an engineer onboard when such situations arise, time is also required to produce a ship that can be used in any environment. Thus, in order to commercialize and disseminate this technology in a short time, it will be necessary to improve system integration to a level that enables judgment by the optimum combination of modules for each ship, and to improve reproducibility under various environments, as recommended in “Report of the Maritime Industry Future Image Study Group” [3].

6. PERSONAL OBSERVATIONS

One year has already passed since the start of the MEGURI 2040 Project, and various points have become apparent. Many of these points would not have been discovered without actually carrying out this work, and the issues that must be addressed have become clear. The author will look forward to seeing the condition when each of these problems has been solved and the experiments are conducted in the second half of FY2021.

On the other hand, many other issues also require study, such as securing redundancy, ensure safety, including the safety of other ships, by communication and mutual cooperation with other ships and navigation traffic control, engine automation, etc. The largest obstacle is economic rationality. The possibility of achieving results that justify the cost is both an old issue and a new one. Considerable costs are incurred in analyzing the functions performed by ship operators and automating each of the analyzed tasks. Referring to Fig. 3, this means obtaining external information not with the human senses, but with existing or newly-developed sensors; developing a system that appropriately selects or rejects, corrects and integrates the sensor values; developing an algorithm that judges what action to take based on those results; and installing a system that gives operational instructions. Ongoing investment is also necessary in order to improve the accuracy of those functions. Can we say that dissemination of this technology is a chicken-and-the-egg problem? Is a different approach needed in order to reduce costs? Is this a problem of the setting of the operational level? Will changes occur depending on the purpose? Hints might be found in the aviation industry, where automatic navigation technology has already been applied practically. Why do the pilots of aircraft use manual operation when taking off and landing, rather than relying on the autopilot function? This may be because there are airports where only manual operation is possible depending on the ground equipment, or for pilot practice, or for psychological reasons, that is, since the pilot must take the final responsibility if an accident occurs, the pilot cannot rely on machines in the high-risk situations of takeoff and landing. Although unmanned commercial airplanes still do not exist, the technical and psychological barriers to the concept of unmanned aircraft are even higher, and those barriers must be understood correctly and confronted head-on. Technologies that cannot be used will be discarded. The shortest road to actual adoption of a technology is not the self-satisfaction of the developer, but imaging the situations in which users will actually use the technology, and addressing those situations one by one.

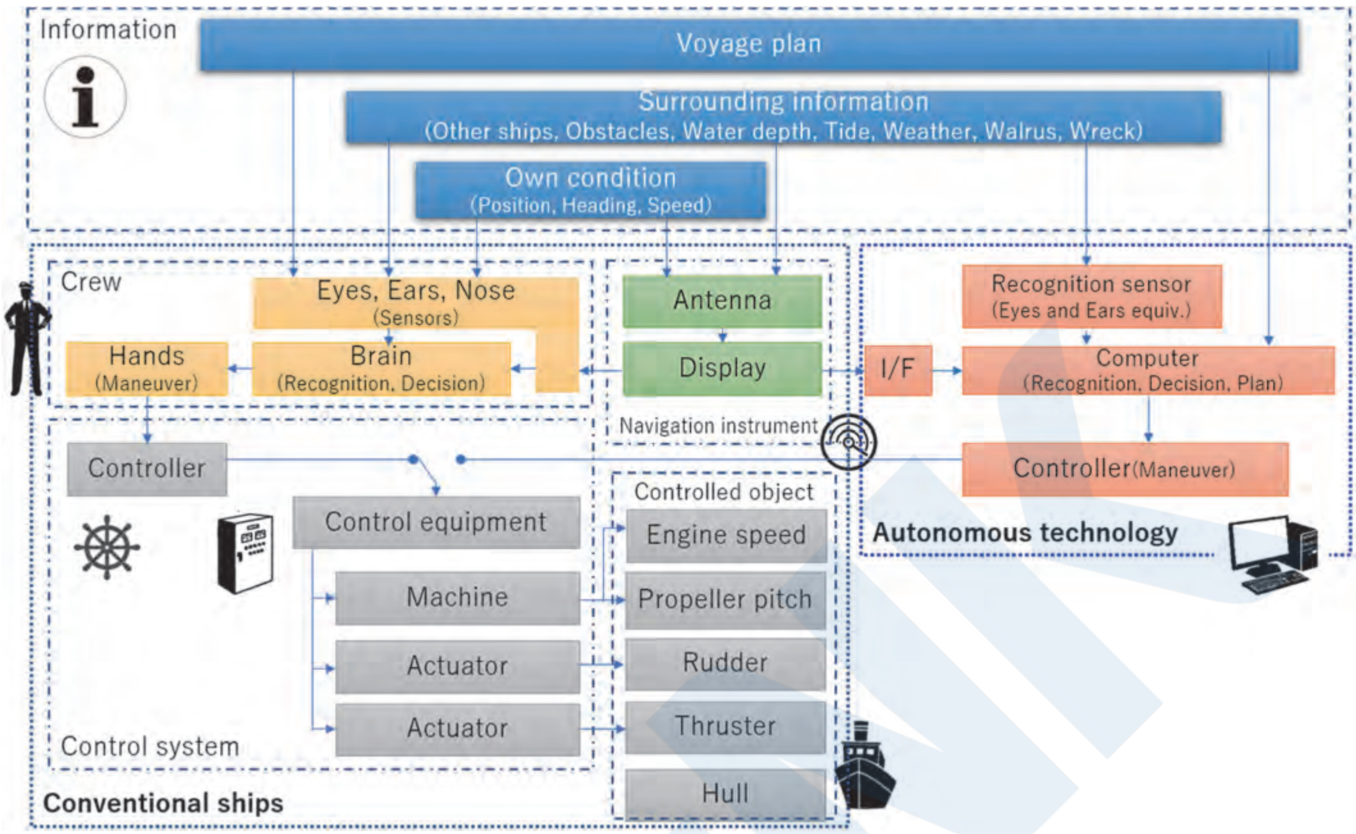

Figure 3 Differences with existing ships in service

7. CONCLUDING REMARKS

The author realizes that this is a prosaic contribution which is quite unsuitable for this Technical Report. Considering the title, I may be criticized for "false advertising." While I accept that criticism, in writing this article, I hoped to respond in some small way to the plain questions of readers concerning why a shipping company is participating in this Project, and what role we are playing.

In the Smart Ship Division of Mitsui O.S.K. Lines, where I work, the stance toward research and development is open innovation. We create new technologies that our company alone cannot produce by bringing together others who have their own respective strengths and roles. We do this for the participating companies, seamen and society. We promote research and development with this belief. Having said that, however, it is not possible to accomplish great things if no budget is available. If you do not try, you will not find out – there are landscapes that you cannot see until you start walking. In the MEGURI 2040 Project, the Nippon Foundation gave us that opportunity. During the remainder of this Project, we hope that we can continue to respond to the cooperation and enthusiasm of all the member companies of the consortium.

ACKNOWLEGMENT

First, I wish to express my heartfelt thanks to the Nippon Foundation for giving us the opportunity to carry out this technical development with the support of the MEGURI 2040 Project.

We also received generous cooperation from the members of the consortium, of course, and also from the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), the Japan Coast Guard, the Maritime Safety Agency offices at the ports concerned, the port administrators and port controllers, fishery cooperatives, and the users of cruisers and fishing boats that use at the ports, among others. I am strongly aware that this experiment was only possible because of sympathizers and supporters of this project, and I would like to take this opportunity to thank all those concerned.

We also received generous cooperation from the ship owners/operators, Imoto Corporation, Imoto Lines and MOL Ferry Co., who adjusted the schedules of the demonstration ships for preparations for the experiment. In particular, I wish to thank the

many seamen who spared their own vacation and rest time to participate in the demonstration experiment.

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Development of Automated Ship Operation Technologies

— MEGURI 2040 Unmanned Ship Demonstration Experiment Project —

Soichiro INOUE*, Hideo MORI*

1. INTRODUCTION

In the field of ship operation, technological development for ship operation support and automation together with the registration and establishment of regulatory framework in the International Maritime Organization (IMO) are underway. In coastal navigation in Japan, the advancing age of seafarers and difficulty of securing seafarers in the future are urgent issues, therefore continuous efforts to improve safety, reduce the workload on crew and strengthen cost competitiveness are necessary. To address these problems, various types of projects in connection with operation support and automated ship operation are being carried out under lead of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and other organizations. As part of those efforts, Mitsubishi Shipbuilding Co., Ltd. is participating in the Joint Technological Development Program for Demonstration Experiments of Unmanned Ships with the Nippon Foundation.

Since the 1980s, Mitsubishi Shipbuilding has experience in commercializing support systems for ship operators called the SUPER ASOS (Advanced Ship Operation Support System) and the Super Bridge-X. The target of the technological level in the present demonstration experiment is the Class II level as defined in the Nippon Kaiji Kyokai (ClassNK) “Guidelines for Concept Design of Automated Operation and Autonomous Operation.”. In the experiment, advanced technologies including AI, image processing and utilization of cloud computing technologies will be installed on a large ferry, and automated operation technologies will be developed and verified, aiming at unmanned ship operation. The category of development are as follows:

1) Automation of port entering and leaving and navigation
2) In-service engine room monitoring and land-based monitoring of operational information

2. SCOPE OF DEMONSTRATION EXPERIMENT

In this demonstration experiment, maneuvering experiments are being conducted with an automated ship with a crew on board over a period of approximately 2 years from February 2020 to March 2022. Basically, development is being carried out targeting the equivalent of level 2 in the above-mentioned ClassNK Guidelines, preconditioned on fallback operation by the crew. A risk analysis is conducted by Class NK in the stage of system design, and the preconditions of operation, preparations and the ODD for conducting a safe demonstration experiment is clarified. It is expected through this demonstration experiment, clarification of the effectiveness of the functions developed for the experiment, their performance limits, and items for future improvement will be identified.

The experiment will be carried out under various environmental conditions when entering and leaving port, navigating in congested waters, and sailing in the open ocean, to verify the effectiveness and accuracy of the functions, system linkage among various devices, ship motion control, influence of marine meteorology and weather conditions, telecommunications, engine room monitoring and onshore monitoring.

3. EQUIPMENT

3.1 Outline of Ship

The ship is a large long-distance ferry used on a coastal route, and is equipped with a 2-shaft CPP in the propulsion system, 2 rudders and bow and stern side thrusters. Table 1 shows the principal particulars and main propulsion equipment.

* Mitsubishi Shipbuilding Co., Ltd.

Table 1　Outline of ship

Ship owner	Shin Nihonkai Ferry Co., Ltd.
Ship operator	Tokyo Kyushu Ferry Co., Ltd.
Shipyard	Mitsubishi Shipbuilding Co., Ltd.
Keel laid Commissioned	August 2020 End of June 2021
Gross tonnage (tons)	15,400 (approx.)
Deadweight (tons)	5,440 (approx.)
Full load displacement (tons)	18,000 (approx.)
Vehicle capacity	12 m trucks: 154 Passenger cars: 30
Passenger capacity	268 persons
Ship dimensions	L (length) = 222.5 m (approx.) B (breadth) = 25 m (approx.) D (depth) = 20.4 m (approx.)
Planned speed (knots)	28.3

3.2　Automated Operation Equipment

This demonstration experiment project will be carried out by adding the equipment developed for automated operation to the normal equipment of the ship, and not by construction of a ship which is fully equipped for automated operation. The equipment installed for this experiment is generically called the Smart Ferry System. The layout of the equipment is shown in Fig. 1.

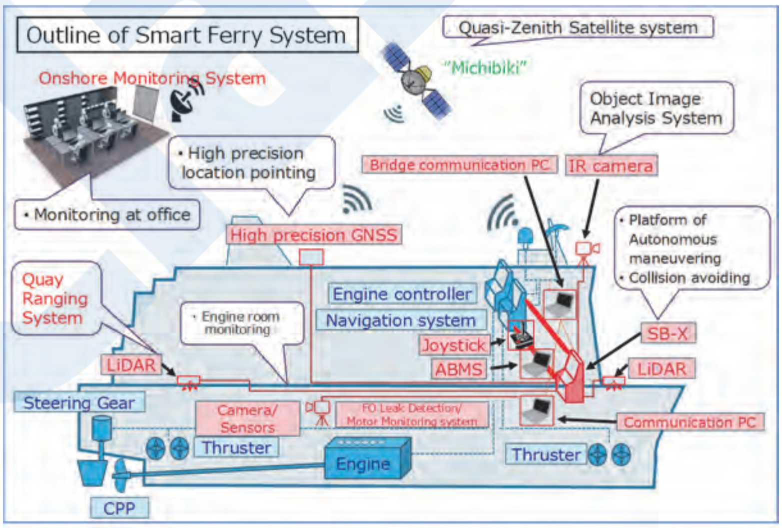

Figure 1　Outline of installation layout of Smart Ferry System

4.　FUNCTIONS OF INDIVIDUAL DEVICES

The essential functions that comprise the system for the unmanned operation demonstration experiment are the navigation-related functions of recognition of other ships, automatic collision avoidance and automatic berthing and unberthing, and the function of remote monitoring for remote condition monitoring of the ship's plant, which comprises the propulsion equipment and its auxiliary equipment. In this project, prototypes of the various devices developed for the Smart Ferry System will be installed, the effectiveness of each device in actual waters will be evaluated by a demonstration experiment, and the subjects for development will be identified from the acquired data.

Table 2 shows an outline of the functions of developed devices.

Table 2 Outline of functions of developed devices in Smart Ferry System

Function	Corresponding system	Outline
Recognition of other ships	Object Image Analysis System	Live video in front of the ship with multiple telescope and wide-angle cameras, performs recognition of other ships, buoys and other objects by AI-based image recognition of the acquired images, and displays the results on a monitor. The direction, distance, velocity and heading direction of the detected objects are calculated from the images and displayed. Target recognition is strengthened in addition to radar and AIS.
Automatic ship navigation	Automatic Maneuvering System	Performs navigation tracking the planned course and time.
Automatic ship collision avoidance	Automatic Maneuvering System	Judges the necessity of collision avoidance corresponding to the operation mode (normal voyage, narrow waterway, etc.) based on the TCPA/DCPA against other ships. The rectangular shape safety territories around the own ship and other ships is taken into considered. In cases where collision avoidance is necessary, the system calculate a collision avoidance course and return course and issues rudder steering commands (speed reduction commands if required).
Automatic ship berthing and unberthing	Autonomous Berthing Maneuvering System	Tracks the planned port entering and leaving courses by actuator control of the AI system, referring to high-accuracy GPS data and gyro data.
Quay ranging	Quay Ranging System	Calculates and displays the distance to the quay, the relative speed and the relative angle by LiDAR units installed on the ship for the hazardous distance and speed alarms.
Remote monitoring	Fuel oil (FO) Leak Detection System	Detects fuel leaks from piping by image analysis.
	Motor Condition Monitoring System	Monitors the currents of motors and performs trend analysis. Used in anomaly prediction and diagnosis of motors.
	Onshore Monitoring System	Transmits maneuvering information, information on the engine section plant, including the above, and engine section alarms obtained in the ship to an onshore office, etc. so the ship's condition can be understood from the land side. The accumulated data are used as data for ship anomaly prediction and maintenance by long-term analysis.

5. FEATURES OF DEVELOPED TECHNOLOGIES

Development in a short term was achieved by integrating the newly developed equipment utilizing AI and image analysis technologies and the ship's normal equipment and devices, and also applying predictive diagnostic technologies owned by this company and its group companies to the ship. The features of these technologies are described below.

5.1 Object Image Analysis System

This system live shoot the area in front of the ship with an infrared camera and automatically classifies the acquired images in real time. The basic system was constructed by photographing ships operating in ports and passing through straits, and then conducting AI machine learning with approximately 10 000 datapoints of learning data. As classifications, objects are classified as ships, buoys, fishing gear and others. It is also possible to successively acquire and add learning data during demonstration experiments.

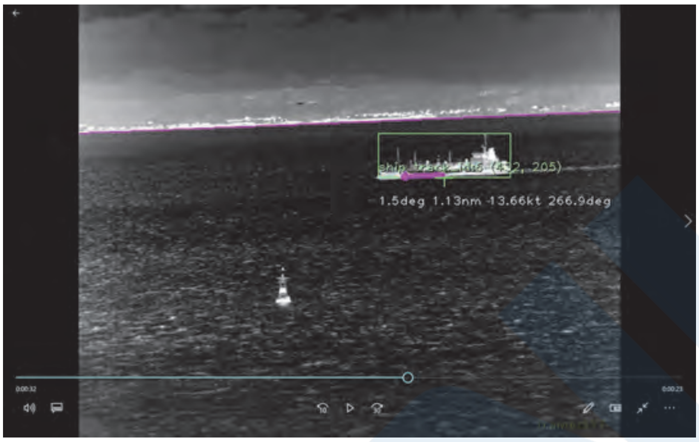

Figure 2　Object Image Analysis System

In order to use these data as information for collision avoidance maneuvering in addition to radar and AIS data, the system is also equipped with a feature that calculates the distance and heading to target objects and the velocity and heading direction of the objects from images. A correction function for ship motion and posture changes is also provided to improve the accuracy of various values calculated from images. Individual data are integrated or separated appropriately in the automatic maneuvering system and used in setting objects of collision avoidance.

The system is also equipped with graphical GUI for display of analysis results.

5.2 Automatic Maneuvering System

In this system, the functions of this company’s navigation support system, which provides information support to the ship operator, were significantly improved to enable automatic tracking of set courses for which unmanned operation is possible, speed control by setting the ship’s target time of arrival, and automatic creation of collision avoidance courses and collision avoidance maneuvering.

Figure 3　Automatic Maneuvering System

Electronic chart is incorporated in the system, and the system is equipped with a tracking function that navigates the ship so as to minimize deviations between the set course and the ship during normal navigation. It also automatically creates courses that avoid shallow waters by setting the safe water depth contour line of the electronic chart, and maneuvers the ship by properly controlling the ship's autopilot and CPP remote controlling gear.

Collision avoidance is a critical issue for automated ship operation technology. This system creates collision avoidance courses by performing calculations for all objects recognized by the ship's radar, AIS and Object Image Analysis System. In setting the range and collision avoidance, the operation patterns, including the collision avoidance range and speed reduction, are changed depending on the navigation mode, i.e., the steady sailing, inland sea, narrow waterway and in-port modes.

The basis of the collision avoidance setting function is calculation of the time and distance to the point of closest approach of all objects and the provisions of the Act on Preventing Collision at Sea. In addition to that, creation of more practical collision avoidance courses has become possible by asking the opinions of operators and captains while conducting simulations of a large number of assumed encounter patterns in the development stage to consider the characteristics of large-scale coastal ferries, and the factors such as the encounter distance in the bow and stern directions and two sides of the ship, the weighting of the priority order of collision avoidance patterns in congested waters, etc. is incorporated in algorithms for collision avoidance.

5.3 Autonomous Berthing Maneuvering System

For large ferries, safety and high-accuracy maneuvering within the limited space of the port is required when entering and leaving ports. In this project, the following composition was used to satisfy these requirements.

1) Highly accurate understanding of the ship's position by the GPS Quasi-Zenith Satellite System (QZSS) and high-accuracy positioning correction (MADOCA: Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis).
2) Use of the ship's position, heading, speed and other navigational information decided by the captain as setting data for entering and leaving port.
3) Operation of actuators by the AI-based maneuvering system, which tracks the above-mentioned course decided by the captain.

It is possible to secure safety and high accuracy by the above 1) and 2), and robust control against external disturbances, etc. is possible by utilizing 3): actuator control by AI for the tracking function.

This AI system was developed by the deep reinforcement learning technique to perform actuator control so as to minimize deviation from the course. This autonomous berthing technology is a new system which has not been reported previously.

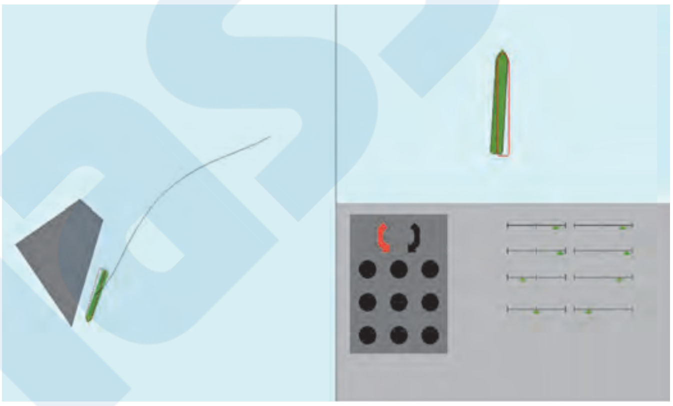

Figure 4　Autonomous Berthing Maneuvering System - Simulation

In large ships, a grasp the ship's response characteristic to steering, that is, a ship motion model, is important. Therefore, a motion model for use in simulations was constructed based on the motion parameters acquired by basin tests using a model of the ship concerned. A berthing/unberthing maneuvering system was developed, and its accuracy was verified by performing actual port entering/leaving operation in a model experiment using the developed system. The robustness of control against wind and waves was also verified in the simulations and model experiment.

Figure 5　Autonomous Berthing Maneuvering System – Model Test

5.4　Quay Ranging System

In this system, small-scale LiDAR units are installed forward and aft on the ship, and the relative distance, relative speed (approach speed of the ship to the quay) and relative attitude of the ship to the quay at medium to close distances are obtained by measurements and calculations based on irradiation of the LiDAR toward the quay. The assumed use of this system is mainly as an alarm during approach. For this experiment, the system was installed on the ship side (rather than the land side) to enable use in any port and to avoid damage by waves, the LiDAR units were mounted at the height of the main deck, which can secure an adequate height above the sea surface. Calculation method of an irradiation angle which are applicable from medium distances to a close distance of 1 meter were developed.

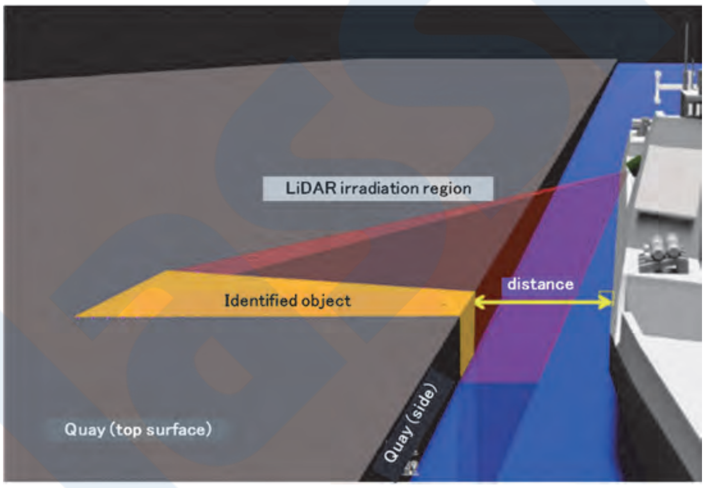

Figure 6　Outline of Quay Ranging System

5.5　FO Leak Detection System and Motor Monitoring System

When considering future automated navigation and unmanned navigation, in addition to automation of voyage maneuvering, it will also be essential to respond to malfunctions of the ship’s equipment. Since automatic repair and recovery of equipment is physically impossible, and installation of redundant equipment for all devices is unrealistic in terms of economy and space, a system which enables preventive maintenance is necessary. A system for condition monitoring and monitoring from shore is the key to this.

The fuel oil (FO) leak detection system utilizes image analysis to detect small fuel leaks, which are the most critical problem for fire prevention in the engine room. The system comprises cameras and an image analysis computational section, and can easily be retrofitted in areas with limited space. The image analysis unit detects fuel leaks as an abnormal condition based on learning of the normal condition. Sensitivity and detection threshold values are set in line with the level of illumination level in the actual environment.

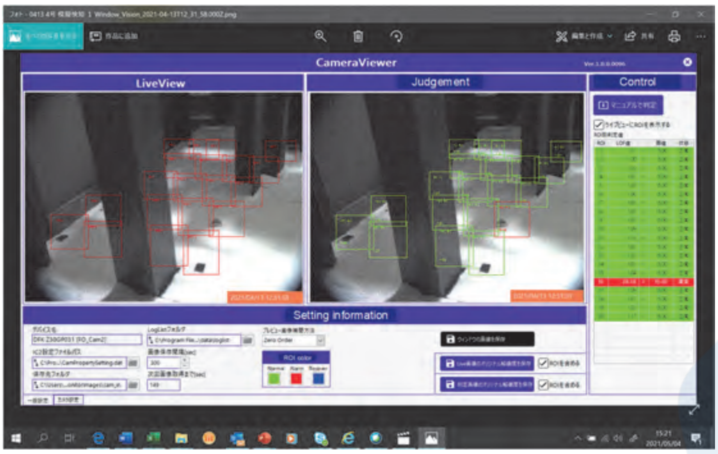

Figure 7　FO Leak Detection System

The motor monitoring system performs anomaly detection by measuring the current from motors, utilizing technology developed for land-based power plants. Continuous data observation by this system can provide a more accurate prediction for motor operation.

Figure 8　Motor Monitoring System - Sensors

Data which will contribute to preventive maintenance based on the characteristics of the ship's plant will also be collected by digitalizing propulsion plant data of the ship in accordance with a M0 checklist.

5.6　Onshore Monitoring System

Monitoring and support from shore will be essential in automated navigation and unmanned navigation. The data from navigation-related sensors and engine section alarms and the data log acquired on the ship are all transmitted as data to a cloud server, and can be accessed from the appropriate webpage. This enables monitoring from any onshore office on the ship operation side, without relying on a dedicated device.

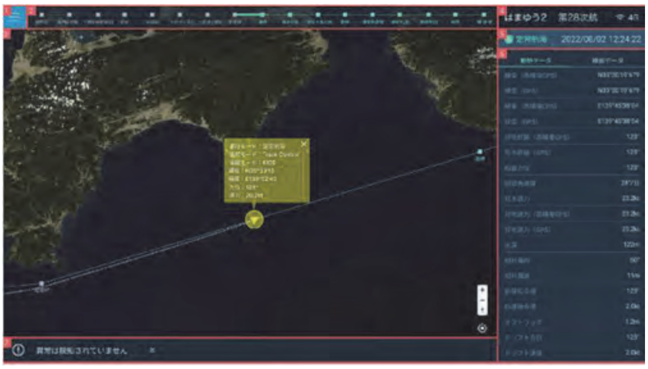

Figure 9　Onshore Monitoring System

Three-dimensional visualization of locations where alarms occur is also possible from designated terminals by using the 3D design data of the engine room.

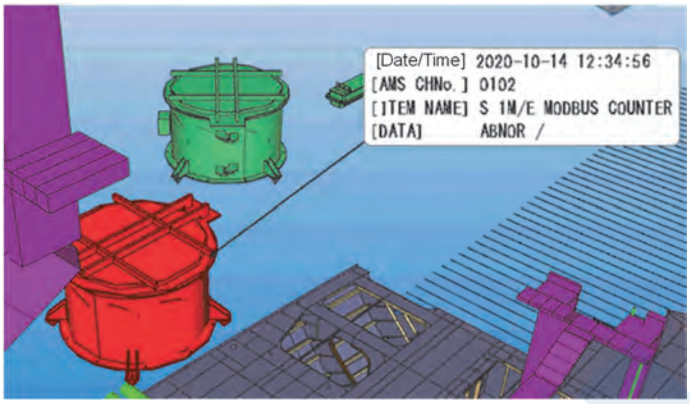

Figure 10 3-D visualization of Alarming part

The problem of cybersecurity is also an important challenge for automated navigation. Although the present case only involves transmission from the ship to a cloud server, and is not intended to perform remote operation of the ship from land, cybersecurity measures were implemented at each location, and the robustness of the safety measures was verified by a penetration test conducted by an outside company specializing in cybersecurity.

6. PURPOSES OF DEMONSTRATION EXPERIMENT AND FUTURE ISSUES

In the demonstration test, various types of measurements and observation and evaluation by the ship's operator will be carried out, contributing to future development.

The evaluation items are ① Comparison with operation by crew, ② Accuracy of operation on an actual ship, ③ Rational linkage with object recognition devices, ④ Effectiveness of onshore monitoring, ⑤ Effective accuracy of sensors and robustness of the maneuvering accuracy under actual marine meteorology and weather conditions.

In addition to the performance improvement of the system described above, it will also be necessary to solve a variety of other problems as future issues for practical application. These include application for operation in various ports with different conditions, development of control method that more closely approximates to the operation by crew, reduction of the cost of the devices, the optical limitations and cost of cameras, linkage of control with the quay side during approaching, and techniques for quick, low cost construction of ship motion models.

Among these efforts, as a technique for automatic planning of courses for entering and leaving various ports, we plan to develop a prototype of a simulation method using the evolutionary computation method CMA-ES, and will verify this technique with the aim of practical application in the future.

7. MEGURI 2040 PROJECT

This project is currently being carried out under the Joint Technological Development Program for Demonstration Experiments of Unmanned Ships with the Nippon Foundation, as part of that organization's "MEGURI 2040" project, in cooperation with the ship's owner, the Shin Nihonkai Ferry Co., Ltd. The development of devices and systems is being carried out with the cooperation of the following universities and companies: Osaka Prefecture University, Osaka University, Brains Corporation, Aidea Inc., Pioneer Smart Sensing Innovations Corporation, MHI Marine Engineering, Ltd. and Kawasaki Heavy Industries, Ltd.

Over the period from 2020 to June of 2021, construction and installation of the various systems on this ship and commissioning and tests will be carried out, followed by the demonstration experiment after the ship enter into service.

Development of Maneuvering System for Realizing Autonomous Ships

— Preliminary Report on Approach Maneuvering Control and Automatic Berthing —

Shintaro MIYOSHI*, Takayuki IOKI**

1. INTRODUCTION

1.1 Background

Accompanying higher speeds in ship-to-shore communications in recent years, there have also been active moves toward digitalization in maritime industries utilizing information and telecommunication and processing and control technologies such as the Internet of Things (IoT) and artificial intelligence (AI). Together with this growing momentum, technology development related to automated and autonomous ship operation has accelerated, resulting in increasingly active concrete moves toward practical application. Particularly in Europe, the ambitious concept of realizing unmanned ships by autonomous ship operation has been proposed, and multiple technology development initiatives are in progress. Various technology development projects are also underway in Japan.

Looking at domestic-trade shipping, which supports approximately 80 % of the transportation of basic industrial materials and products in the Japanese domestic economy, the number of veteran seafarers is decreasing, and their average age is increasing. As shown in Fig. 1, Composition of domestic seafarers by age [1)], the percentage of persons over 50 years old exceeds 37 %, and the largest age group of sailors is shifting to 60 years and older. Moreover, since 70 % to 80 % of maritime accidents in the waters around Japan are caused by human factors, reducing the risk of accidents at sea by preventing human error is critical for securing transportation quality.

Thus, in view of the current shortage of seafarers and the rapidly aging, prevention of human error by improving the working environment and reducing the workload on sailors is an urgent challenge.

Technology development aimed at realizing autonomous ships is one effort to address this social situation. The start of the Nippon Foundation's MEGURI 2040 Project [2)], which aims at the future goal of completely unmanned ship operation, has accelerated technology development for automated and autonomous ship operation.

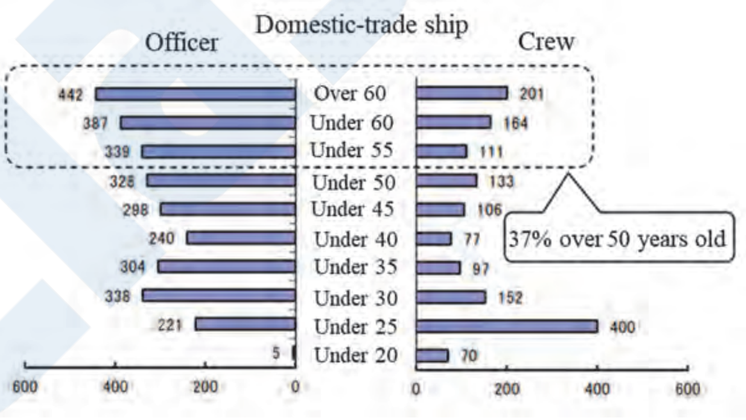

Figure 1 Composition of domestic seafarers by age

1.2 Overview

The Mitsui E&S Group, of which the authors are members, Mitsui O.S.K. Lines, Ltd. and the Tokyo University of Marine Science and Technology, jointly carried out the "Safety of Automatic Berthing and Un-Berthing Demonstration Project" of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) under a 3 year plan beginning in 2018. The Mitsui E&S

* Mitsui E&S Shipbuilding Co., Ltd.
** Akishima Laboratories (Mitsui Zosen) Inc.

Group was also involved in the development of an autonomous maneuvering system as part of the two consortia “Autonomous navigation at Sarushima, Yokosuka” and “Verification testing of unmanned technologies using coastal container vessels and car ferries” in the MEGURI 2040 Project of the Nippon Foundation (Public Interest incorporated Foundation).

In ship operation, maneuvering always requires a total evaluation, judgment of the situation, and decision-making based on information on the waters and ships navigating nearby, which is acquired by visual observation, radar, AIS (Automatic Identification System) and instruments, as well as various other information, including weather and marine meteorological conditions, the operating condition of the ship’s engines and related laws and regulations. In particular, when maneuvering in a port, it is necessary to simultaneously operate multiple steering devices (including the rudder, propellers, and thrusters) based on topographical restrictions such as the water depth, course, etc.It is also especially important to consider the control characteristics of the ship at reduced speeds because the effects of external disturbances are relatively larger under these conditions.

The Mitsui E&S Group was involved in the development of the joystick maneuvering control system, the Mitsui Ship Maneuver Control System (hereinafter, MMS) and the Dynamic Positioning System (DPS) [3],, which has been installed on approximately 100 ships. Possessing a high level of maneuvering motion, control technology, and particularly technology related to maneuvering motion control a at low speeds. Utilizing these technologies, we are developing a maneuvering control system for realizing autonomous ships.

This paper presents an overview of the development of the maneuvering system and automated approach maneuvering control, which is the most difficult process in port maneuvering systems, and a preliminary report describing some of the results of approach and berthing maneuvering control in a demonstration test conducted at an actual quay using an actual ship.

2. OVERVIEW OF DEVELOPMENT OF AUTONOMOUS MANEUVERING SYSTEM

2.1 Condition Setting

In order to construct a maneuvering system, which is indispensable for realizing autonomous ships, various conditions were set, including the purpose and targets of the system and the operating conditions and requirements of the developed system. The conditions summarized below.

- System shall realize automation and autonomous operation of work for ship navigation which is performed from the bridge.
- The purpose of the system shall be hands-free berth-to-berth navigation based on the given voyage plan.
- The crew shall be able to understand the conditions of the own ship and its surroundings at all times.
- The crew shall perform fallback when conditions are outside the limit region of the system or when safe navigation cannot be maintained.
- The system shall also function without support from land.
- The system shall consider commercialization.
- Fallback is required, because redundancy in case of equipment failure is not considered in order to hold down the product cost.
- Installation on ordinary ships and retrofitting on existing ships shall be possible.
- It shall be possible for the crew to maneuver with the existing maneuvering devices by one action.
- In particular, the control right of the actuators shall be clear, preconditioned on input from the existing sensors and devices and output to the existing actuators.
- The system shall be connected considering the safety of the shipboard equipment.
- Regions limited by weather and marine meteorology shall be set based on the performance of the individual ship and the waters of each voyage.

2.2 Functions Required in Maneuvering System

In order to identify the functions required in an autonomous maneuvering system for realizing autonomous ships, the work performed by the crew on the bridge was investigated. Next, the functions required in the autonomous maneuvering system were extracted from the investigated work, considering the set conditions mentioned in the previous section. Focusing on the flow of information for realizing those functions, four main tasks were formulated below. The representative tasks classified in each function are shown in Table 1.

- Navigation state control
- Situational awareness
- Automatic collision avoidance (navigation and course plan management)
- Maneuvering control

Table 1 Tasks and functions required in maneuvering system

Task	Subtask Level 1	Subtask Level 2
1. Navigation state control	1.2 Judgment of possibility of autonomous maneuvering control	1.2.2 Judgment by system
	1.3 Mode control	1.3.1 Target WP control
		1.3.2 Mode transition (deberthing maneuvering → in-port maneuvering)
		1.3.3 Mode transition (in-port maneuvering → out-of-port maneuvering)
		1.3.4 Mode transition (out-of-port maneuvering → in-port maneuvering)
		1.3.5 Mode transition (in-port maneuvering → berthing maneuvering)
		1.3.6 Collision avoidance maneuvering control
2. Situational awareness	2.1 Watchkeeping	2.1.1 Grasp of other ships as moving or stopped
		2.1.2 Grasp of navigated waters
		2.1.3 Grasp of drifting objects, etc.
		2.1.4 Judgment of danger of grounding
	2.2 Situational awareness of ship navigation	2.2.1 Own ship's position
		2.2.2 Grasp of own ship's motion
	2.3 Weather and marine meteorology observation	2.3.1 Wind direction and speed
	2.4 Situational awareness of ship operation	2.4.1 Grasp of condition of main engine operation
		2.4.2 Grasp of condition of electric power on ship
	2.5 Evaluation of actuator response	2.5.1 Grasp of condition of actuators
		2.5.2 Evaluation of response values
	2.6. System soundness control	2.6.1 Monitoring of system operating condition (monitored by the system)
	3.2 Confirmation of course	3.2.1 Confirmation of appropriateness and safety
		3.2.4 Control of executed planned course
4. Automatic collision avoidance	4.1 Navigation space (waters) risk calculation	4.1.1 Setting of course environment
		4.1.2 Setting of topographical/water surface environment
		4.1.3 Calculation of risk of collision with other ships
		4.1.4 Calculation of total navigation risk
	4.2 Collision avoidance plan	4.2.1 Setting of collision avoidance plan
		4.2.2. Setting of collision avoidance course
		4.2.3 Evaluation of set course
5. Maneuvering control	5.1 Berthing and un-berthing maneuvering (berthing)	5.1.1 Calculation of maneuvering plan
		5.1.2 Maneuvering control
	5.2 In-port maneuvering (disapproach, approach)	5.2.1 Calculation of maneuvering plan
		5.2.2 Maneuvering control
	5.3 Out-of-port maneuvering	5.3.1 Maneuvering control
	5.4 Estimation of external force	5.4.1 Estimation of fore/aft external force
		5.4.2 Estimation of lateral external force
		5.4.3 Estimation of turning direction external force
		5.4.4 Estimation of steady course deviation component
		5.5.5 Estimation of wind pressure
	5.5 Situational awareness/evaluation of control	5.5.1 Evaluation of control results
		5.5.2 Prediction of control results
		5.5.3 Evaluation of GNSS error factors

2.3 System Configuration

In constructing the autonomous maneuvering system, the Mitsui Ship Maneuver Control System (MMS) mentioned in Chapter 1 was used in order to reduce the cost and time of development. The MMS has already received ship classification and has a linkage function with nautical instruments and functions for safely controlling maneuvering devices (propellers, rudder, thrusters, etc.). Because this system realizes various control functions, including joystick maneuvering, heading-keeping and dynamic positioning, it was thought that development time and costs could be substantially reduced, while simultaneously constructing a highly reliable control system.

In addition, the system also enables maneuvering by a single operator using only a joystick and dial, which is extremely effective when transferring control from the system to a human ship operator.

As shown in Fig. 2, Configuration of autonomous maneuvering system, a maneuvering system for realizing autonomous maneuvering was developed by providing a function that connects the autonomous maneuvering control system, which performs the control calculations for autonomous maneuvering, to the MMS.

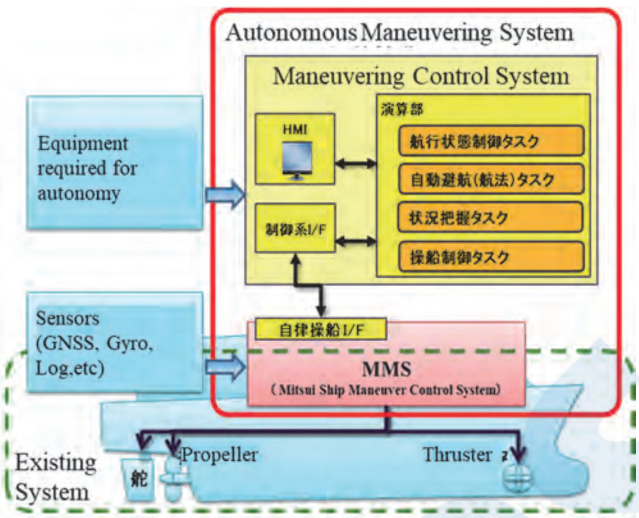

Figure 2　Configuration of autonomous maneuvering system

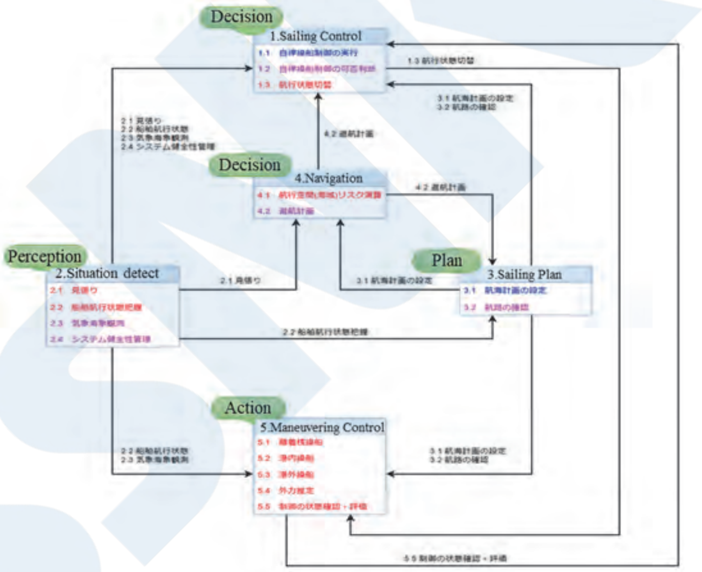

Figure 3　Task block diagram of autonomous maneuvering control functions

The autonomous maneuvering system comprises the "Autonomous Maneuvering Control System," which performs the control calculations for autonomous maneuvering, and the MMS, which is equipped with an interface with the newly-developed autonomous maneuvering system. The system realizes autonomous maneuvering by transferring the sensor and other information input by the MMS to the Autonomous Maneuvering Control System, and controlling the various actuators, that is, the rudder, propellers and thrusters, from the MMS in accordance with the control commands calculated by the Autonomous Maneuvering Control System.

Next, the tasks for realizing the functions required in the maneuvering system, as analyzed in the previous section 2.2, and the dataflow between the tasks are shown in Fig. 3, Task block diagram of autonomous maneuvering control functions.

3. MANEUVERING CONTROL SYSTEM

3.1 Overview of Maneuvering Control System

Depending on the phase of ship operation, maneuvering can be classified as out-of-port maneuvering, which includes navigation in open waters and along coastlines, and in-port maneuvering, which means navigation inside a port or harbor. In-port maneuvering can be subclassified as unberthing, disapproach, navigation at steady speed (including narrow waterways), approach and berthing. Because the content and motion considered in each of these phases differ greatly, it is not realistic to control all operations by the same logic. Therefore, control logics suited to the respective phases are used. In this paper, we will explain approach maneuvering control, as this phase has a high degree of difficulty among the above-mentioned phases, and thus has a high possibility of resulting in a maritime accident.

3.2 Approach Maneuvering Control

As features of approach maneuvering, a ship generally must be navigated in waters with topographical restrictions such as channels or breakwaters, while controlling the ship position and bow heading toward the berthing point during deceleration.

In particular, the challenges for realizing approach maneuvering control include the fact that approach must be successful on the first attempt, as redoing the approach is difficult under the above-mentioned topographic restrictions, and the ship's motion characteristics continue to change significantly due to deceleration, and at the same time, the relative effects of external disturbances become larger due to the decreased speed of the ship.

3.2.1 System Configuration

Approach maneuvering cannot be automated by a simple control function because it is not possible to redo the approach and the ship's motion characteristics and influence of external disturbances change due to deceleration. Therefore, a combination of multiple algorithms was developed, referring to the shiphandling of actual ship operators, in order to realize approach maneuvering control.

A list of the control algorithms is shown below, and a block diagram is presented in Fig. 4.

- Navigation filter
- Track Control filter(TCS Filter)
- Feedback track control(TCS F.B. Control)
- Feedforward to steady external force
- Predicted maneuvering feedforward control
- Ship velocity control

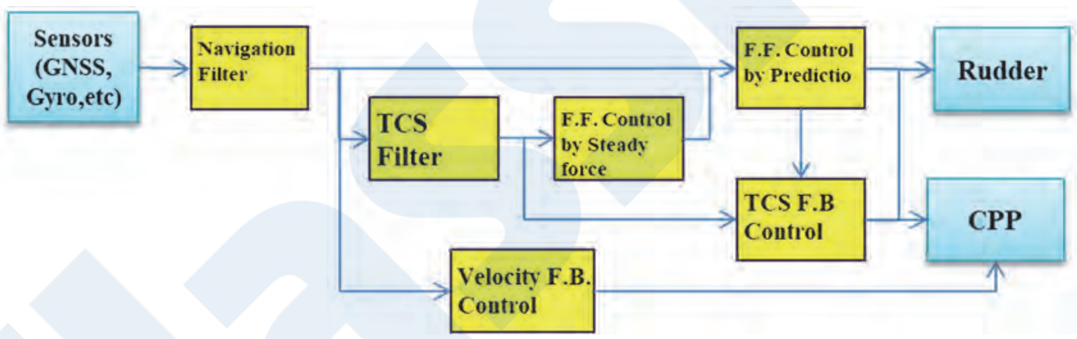

Figure 4　Block diagram of approach maneuvering control functions

3.2.2 Navigation Filter

Positioning error is small in this system because a RTK (Real Time Kinematic) positioning GNSS receiver is used. However, because the positioning signals contain a noise component, which is considered to have a significant effect, it is necessary to differentiate the position information when calculating ship's ground speed (absolute speed). In order to estimate the ship's probable position and speed smoothly, a linear Kalman filter called a navigation filter was adopted. This filter was also used by Imamura [4)] and Tamaru [5)].

As shown in Fig. 5, a 2 dimensional coordinate system fixed with respect to the earth is defined, in which the origin is the reference waypoint (WP)¸ and the northerly and easterly directions are the positive directions of the X axis and Y axis, respectively. The ship's position x_n is defined as follows by using the ship's position, speed and acceleration on the defined coordinate system at time t_k as state variables in Eq. (1). (In the following, the superscript T denotes a transposed matrix.)

$$x_n = [p_x(n), p_y(n), v_x(n), v_y(n), a_x(n), a_y(n)]^T \quad (1)$$

The state space expression, comprising the state equation and observation equation, are obtained from the above, as follows:

State equation = $x(n+1) = \mathrm{F}x(n) + G\omega(n)$
Observation equation = $y(n) = \mathrm{H}x(n) + v(n)$ (2)

$$\mathbf{F} = \begin{bmatrix} 1 & 0 & \Delta T & 0 & \Delta T^2/2 & 0 \\ 0 & 1 & 0 & \Delta T & 0 & \Delta T^2/2 \\ 0 & 0 & 1 & 0 & \Delta T & 0 \\ 0 & 0 & 0 & 1 & 0 & \Delta T \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \ \mathbf{G} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

F, G and H are the state transition matrix, driving matrix and observation matrix, respectively. Here, the first element of $y(n)$ is the latitude information obtained from the Kalman filter, and the second element is the longitude. When these two signals have been obtained by using the Kalman filter, the estimated values of the ship's position, speed and acceleration are obtained in the internal expression in Eq. (2), and the smoothed ship position and speed can be obtained.

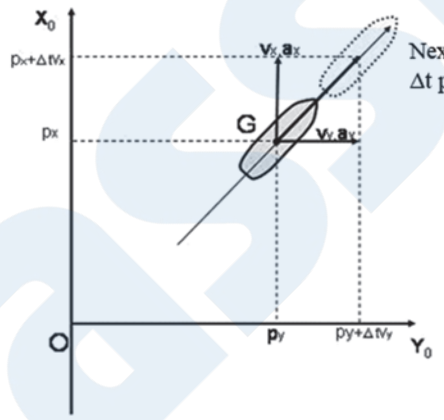

Figure 5 Coordinate system in navigation filter

3.2.3 Track Filter

In order to realize approach maneuvering control, approach maneuvering is defined as a track control problem for keeping the set approach line, and a Kalman filter is used in estimation of the state variables in the state space expression obtained from the maneuvering motion model, as in the optimal tracking control proposed by Miyoshi [6) 7)].

In the track control filter, the ship's lateral velocity: v, angular velocity (yaw rate): r, error of bow heading from the target course (yaw angle): φ, cross track error: Y_d (as the deviation of the own ship's position from the target course) and the rudder angle: δ shown in the coordinate system in Fig. 6 are adopted, and the motion model for control shown in Eq. (3 is used. Here, the technique for obtaining a_{11}, a_{12}, a_{21}, a_{22}, b_{11} and b_{21} in Eq. (3) from the linearized maneuvering motion model according to Miyoshi [6) 8)] was also adopted because it is possible to obtain the motion model from the ship's principal particulars, which is an advantage from the viewpoint of generalization and commercialization.

$$\begin{pmatrix} \dot{v} \\ \dot{r} \\ \dot{\varphi} \\ \dot{Y}_d \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & U_0 & 0 \end{pmatrix} \begin{pmatrix} v \\ r \\ \varphi \\ Y_d \end{pmatrix} + \begin{pmatrix} b_{11} \\ b_{21} \\ 0 \\ 0 \end{pmatrix} \delta \qquad (3)$$

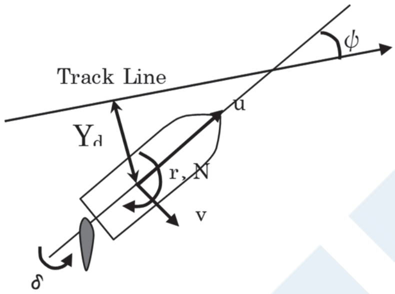

Figure 6 Coordinate system of motion model in track control

From the continuous linear model shown in Eq. (3), the discretized model at a sampling time Δt is calculated by Eq.(4):

$$\mathbf{\Phi} = e^{\mathbf{A}\Delta t} \qquad \mathbf{\Gamma} = \mathbf{B}\int_0^{\Delta t} e^{\mathbf{A}\Delta t} dt \qquad (4)$$

As a result, the following discrete expression is obtained in Eq. (5).

$$\mathbf{x}(n+1) = \mathbf{\Phi}\mathbf{x}(n) + \mathbf{\Gamma}\mathbf{u}(n)$$

$$\mathbf{\Phi} = \begin{pmatrix} \Phi_{11} & \Phi_{12} & 0 & 0 \\ \Phi_{21} & \Phi_{22} & 0 & 0 \\ \Phi_{31} & \Phi_{32} & 1 & 0 \\ \Phi_{41} & \Phi_{42} & \Phi_{42} & 1 \end{pmatrix}, \quad \mathbf{\Gamma} = \begin{pmatrix} \Gamma_{11} \\ \Gamma_{21} \\ \Gamma_{31} \\ \Gamma_{41} \end{pmatrix}, \qquad (5)$$

$$\mathbf{x}(\mathbf{n}) = [v \quad r \quad \phi \quad \mathrm{Y_d}]^t, \quad \mathbf{u}(n) = \delta(n)$$

In order to treat steady external force, the lateral displacement velocity d_Y from the target course is added to the state variable in Eq. (6).

$$\mathbf{x}(n) = [v(n) \quad r(n) \quad \phi(n) \quad \mathrm{Y_d}(n) \quad d_Y(n)]^t \qquad (6)$$

As shown in the state equation in Eq. (7), in the final line of the system expression, the cross track error is expressed as having a steady nature.

State equation

$$\mathbf{x}(n+1)=\begin{pmatrix}\Phi_{11} & \Phi_{12} & 0 & 0 & 0\\ \Phi_{21} & \Phi_{22} & 0 & 0 & 0\\ \Phi_{31} & \Phi_{32} & 1 & 0 & 0\\ \Phi_{41} & \Phi_{42} & \Phi_{43} & 1 & \Delta t\\ 0 & 0 & 0 & 0 & 1\end{pmatrix}\begin{pmatrix}v(n)\\ r(n)\\ \psi(n)\\ Y_d(n)\\ d_y(n)\end{pmatrix}+\begin{pmatrix}\Gamma_{11}\\ \Gamma_{12}\\ \Gamma_{13}\\ \Gamma_{14}\\ 0\end{pmatrix}\delta(n)+\boldsymbol{\varepsilon}(n) \qquad (7)$$

Observation equation

$$\mathbf{y}(n)=\mathbf{Hx}(n)+w \quad \mathbf{H}=\begin{pmatrix}0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\end{pmatrix} \qquad (8)$$

H: observation matrix, ε: system noise, *w*: observation noise

Ship motion related to tracking was estimated by estimating the state variables in this state space expression by using the Kalman filter.

However, because the model includes terms that depend on the ship's speed, it cannot be adapted to the problem of approach maneuvering in its present form, since a ship's speed changes greatly from the start to the end of approach. Therefore, a tracking model using multiple ship speeds was designed, and the estimated values of the state variables for the corresponding speeds were obtained by using a model in which the models for each speed are treated as membership functions.

3.2.4 Feedback Track Control

To realize approach maneuvering control, feedback control was performed by using the state variables mentioned in the previous section. Concretely, the amount of rudder action u(*n*) was obtained by multiplying the state variable x(*n*) by the control gain L(*n*), as shown in Eq. (9).

$$\mathbf{u}(n)=-\mathbf{L}(n)\mathbf{x}(n) \qquad (9)$$

Here, the general technique is to obtain the optimal value of L(*n*) by using an evaluation function. However, in the present study, L(*n*) was decided by trial-and-error by performing simulations due to the large number of uncertain elements such as changes in the ship's speed.

3.2.5 Feedforward For Steady External Force

As discussed up to this point, it is also important to consider the external force acting on a ship in approach maneuvering control because the effect of external forces increases as the ship's speed decreases. Therefore, feedforward control for steady external force [8] was added to this control method by using the lateral displacement rate from the target course d_Y, which was calculated by the Kalman filter as described in section 3.2.3.

As shown at the left in Fig. 7, a ship which is underway with tracking as a speed U in the composite direction of the lateral speed d_Y and the longitudinal speed u. Under this condition, the ship's direction shifts to a direction having an angle of φ_S from the bow heading. Because φ_S is very small at this time, it can be assumed that $d_Y \fallingdotseq d_Y'$, and it is possible to reduce the steady course error, as shown at the right in Fig. 7, by considering the φ_S when the declination φ of the bow heading from the target course changes to the optimal control law. Concretely, it is possible to consider steady external forces by considering this φ_S by predictive maneuvering feedforward control, as described in the following section.

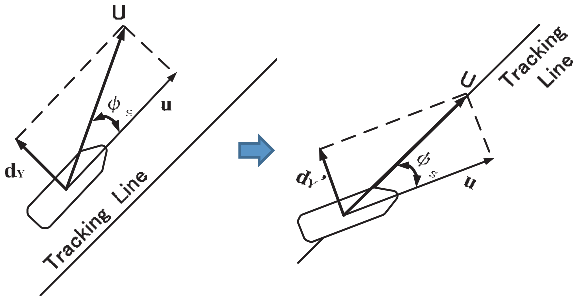

Figure 7 Image of control for steady external force

3.2.6 Predictive Maneuvering Feedforward Control

A ship operator generally performs maneuvering not only considering the current deviation from the target course, but also by predicting the own ship's position and heading several 10 s to several minutes in the future. To date, a number of studies [9) 10) 11)] have been done on berthing maneuvering, but all of those studies proposed that it is necessary to apply feedforward control considering the predictive maneuvering normally performed by ship operators in the maneuvering phase of approaching the berth while reducing speed.

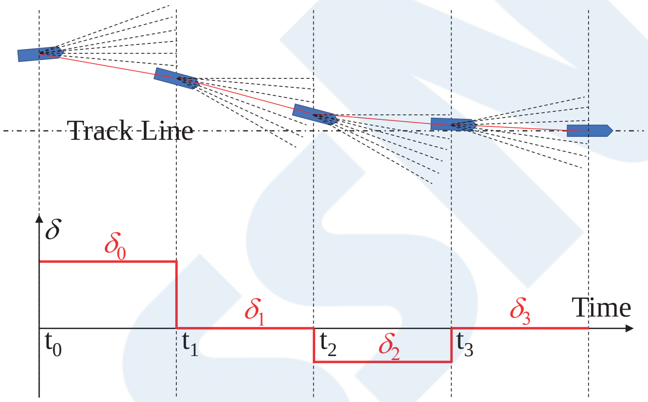

Figure 8 Image of shooting method search

In this type of predictive control, the deep learning method [12)] or similar techniques are conceivable. However, due to the long time required to collect the teaching data, the authors decided to obtain the optimal steering plan by using the shooting method in consideration of practical application.

As shown in the image of this search method in Fig. 8, the optimal rudder angle for returning to the target course is calculated while changing the rudder angle multiple times from the starting point. In this image, the optimal rudder angle for returning to the target course is searched by changing the rudder angle at set time steps from the state when the cross track error on the left edge of Fig. 8 occurs.

The procedure of this search technique using the shooting method is as follows.

① Prepare a high speed simulation using an MMG (Maneuvering Modeling Group) model.

② Prepare combinations of n times of changes for candidate rudder angles δ while maintaining a time of T seconds.
(Example)
δ [deg] = {±15.0, ±10.0, ±5.0, ±2.5, 0.0}
T [s] = 30, n = 4

③ Search for the optimal combination by using the high speed simulation.
Definition of "optimal": To minimize the evaluation function shown in Eq. (10)

$$J = \sum_{i=0}^{n} \left(q^{n-i} \left(W_y Y_{d,i}^2 + W_\psi \Delta\psi_i^2 + W_r r_i^2 \right) + W_\delta \delta_i^2 \right) \qquad (10)$$

q: damping factor
W: weightings
$Y_{d,i}$: cross track error at completion of i-th step
$\Delta_{\psi i}$: heading error (yaw) at completion of i-th step
r_i: turning angular velocity at completion of i-th step
δ_i: rudder angle in i-th step

At this time, the heading considering φ_S, which was obtained in the previous section, was used as the reference course heading when obtaining $\Delta_{\psi i}$.

4. DEMONSTRATION TEST

A demonstration of the approach and berthing control was carried out with an actual ship at an actual berth by using a port maneuvering control system which combined the approach control described up to this point and berthing control applying DPS, *etc*. This chapter presents an overview of the demonstration test as a preliminary report on the demonstration.

This demonstration test was conducted jointly with Mitsui O.S.K. Lines and Tokyo University of Marine Science and Technology, which participated in the "Safety of Automatic Berthing and Un-Berthing Demonstration Project" of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Prior to the test at the actual quay, a virtual quay was set outside the port, and the actual test was carried out after verifying that the control functions of the system were sufficient.

4.1 Test Conditions

4.1.1 Test Ship

The ship used in the demonstration was the car ferry *Sun Flower Shiretoko*, which is owned and operated by MOL Ferry Co., Ltd. The principal particulars of the test ship are shown in Table 2, and a photograph is shown in Fig. 9.

Table 2 Principal particulars of *Sun Flower Shiretoko*

● Gross tonnages	11 410 t
● Length overall (LOA)	190.0 m
● Length between perpendiculars (LBP)	175.0 m
● Breadth moulded	26.4 m
● Depth moulded	20.5 m
● Draft (designed full load)	6.85 m
● Maximum speed in test operation	25 Kts
● Maximum passenger capacity	180
● Main engines	4 cycle medium speed diesel × 2 units 14 580 kW × 400 rpm (/unit)
● Propellers	CPP × 2 shafts
● Thrusters	Bow × 2 units Stern × 1 unit

Figure 9 General view of car ferry *Sun Flower Shiretoko*

4.1.2 Test Waters and Maneuvering Scenarios

The test was conducted at the Port of Oarai, Ibaraki Prefecture and Central West Quay berth. The maneuvering scenario used in the test is shown in Fig. 10. The target berthing point was before the berthing point used in normal service, and was set so as to secure clearances with the wharf of 25 m at the front of the ship and 10 m on the starboard side.

Figure 10 Maneuvering scenario used in demonstration test

4.1.3 Test Conditions

Table 3 shows the weather and marine meteorological conditions, etc. when the demonstration test was conducted. The test was started at an initial speed of 12.0 kts from a point 1.0 miles before the initial WP (waypoint) near the tip of the offshore breakwater at the Port of Oarai, as shown in Fig. 10.

Table 3 List of conditions of demonstration test

Weather and marine meteorology conditions	
Weather	Clear
Visibility	Good (approx. 12 miles)
Wind	NE to ENE
Wind speed (outside port)	10.0 to 14.0 m/s
Wind speed (inside port)	4.5 to 10.0 m/s
Wave height (outside port)	1.5 m
Wave direction (outside port)	NE
Other conditions	
Test time	Afternoon
Draft	6.4 m

4.2 Test Results

A total of 4 demonstration tests were carried out at the actual quay. The results of all the tests confirmed that course-keeping and deceleration in accordance with the predetermined maneuvering scenario were possible, and the ship could stop (ship speed < 0.1 kts) with an accuracy of 0.5 to 2.0 m from the target berthing point.

As one example, Fig. 11 shows the ship track chart and Fig. 12 shows time-series screens of the test system. Because this paper is a preliminary report, the explanation of the time-series information will be omitted here.

As can be understood from the track chart, it was found that the ship meanders when passing between the offshore breakwater, the port breakwater and the breakwater on the inner side. This phenomenon was not observed in the simulation or the test with the virtual breakwater outside the port. The cause of meandering in the actual test is considered to be the large effect of environmental changes, including the large change in the wind speed due to the shielding effect of the breakwaters, and local currents generated between the breakwaters.

4.3 Discussion

The effectiveness of the maneuvering control system developed up to this point could be confirmed in this demonstration test. On the other hand, the results also showed anew that ship motion is greatly influenced by changes in external forces due to the effects of topography at an actual port and actual quay, and at the same time, a control system which is capable of adapting quickly to changes in external forces is required.

The results confirmed that some differences appeared between predictive maneuvering (results of shooting) and in actual ship motion during the demonstration test. Where this is concerned, it is thought that the maneuvering motion model itself had changed due to the effect of shallow water because the water depth becomes shallow and under keel clearance (UKC) decreased to only 0.8 to 1.5 m when the ship entered the port. Thus, the results of this test confirmed the need to study countermeasures.

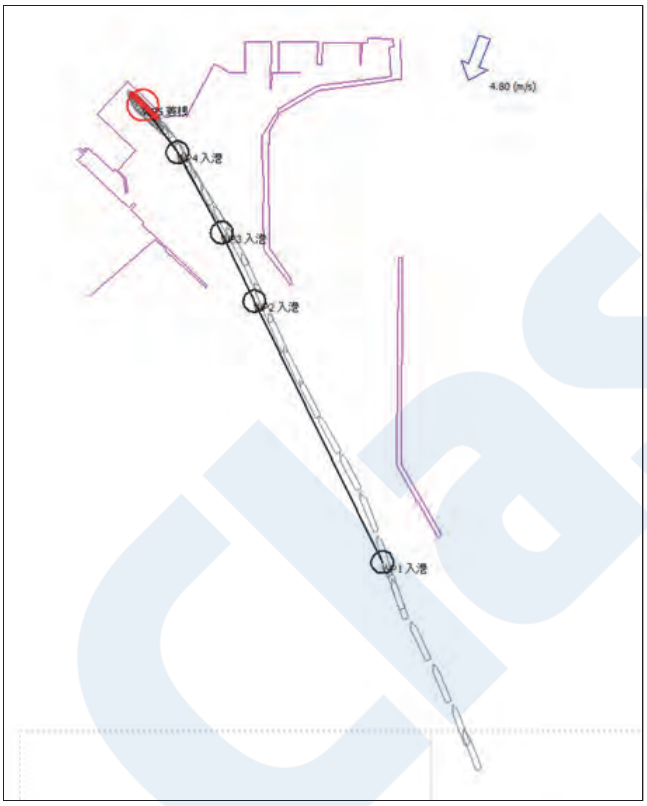

Figure 11　Track of demonstration test

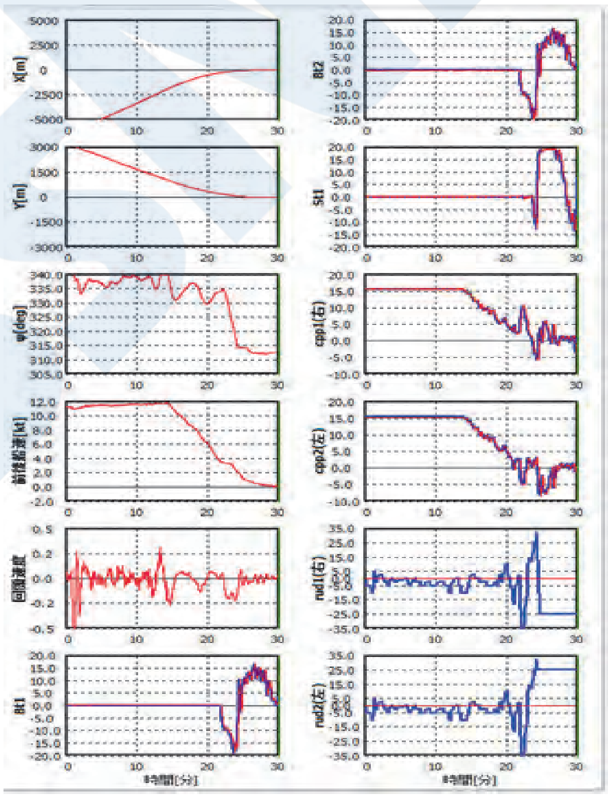

Figure 12　Time-series screens of test system

5. CONCLUSION

An automated maneuvering system is indispensable for realizing autonomous ship operation. In this paper, the requirements of this system were presented, followed by an overview of the conceptual design and basic design.

The automated maneuvering control system which controls the movement of the ship is a key function of the maneuvering system. Next, therefore, the composition and technology of the maneuvering control system are explained, with a particular focus on approach maneuvering control.

Finally, as a preliminary report, the results of a demonstration test of approach and berthing maneuvering control at an actual quay by an actual car ferry using the in-port maneuvering control system incorporating the approach maneuvering control and berthing maneuvering control functions explained previously are presented.

This study confirmed the effectiveness of the maneuvering system which is currently being developed with the aim of realizing autonomous ship operation. However, at the same time, various problems also became clear.

In the future, the authors will continue to conduct technology development for practical application of an automated maneuvering system for autonomous ship operation by conducting technology development centering on maneuvering control and clarifying the problems for safety and practical application by simulations and actual ship tests. We also hope to contribute to the maritime industry of Japan by realizing practical application of autonomous ships at the earliest possible date through cooperation with companies that possess related technologies, including manufacturers of navigation instruments.

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Safety Evaluation for Technologies related to Autonomous Ships

Tomoaki YAMADA*

1. INTRODUCTION

1.1 Background

In recent years, technologies such as sensing technology, AI and IoT have made rapid progress and are used in various fields. In the field of ships, research and development of technology related autonomous ships has been actively carried out globally with the aim of improving safety by preventing human error and improving working conditions by reducing the workload on crew. It has already moved from the research stage to the development stage, and some concrete development projects have been launched all over the world. In Japan, the demonstration projects by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) for the three functions of automatic maneuvering function, remote ship maneuvering function, and automatic berthing and unberthing function have been completed in FY2020. The findings obtained from these projects are being summarized. In addition, as represented by the unmanned ship project MEGURI 2040 by The Nippon Foundation, multiple projects have been launched, aiming to put the autonomous ship into practical use by 2025 from both the rule development and technological development.

1.2 Target for Autonomy (Automation/Remote Control)

There are a wide variety of onboard operation on a ship. Therefore, it is necessary to clarify which onboard operation is targeted at first.

The onboard operations can be roughly divided into two departments, deck department and engine department (see Table 1). At the moment, technologies related to automation and remote control of onboard operation related to deck department, especially for navigation task at W/H, is being developed.

Regarding the engine department, technological development related to CBM (Condition Based Maintenance) is advanced with the aim of reducing onboard maintenance work. Since the introduction of these technologies into autonomous ship is being considered, the consideration of autonomous operation of the engine department has come to the agenda recently.

Table 1 Outline of onboard operation

Deck department	Navigation (lookout, radio communication, steering, etc.) Port entry/departure-related (preparation work, mooring/unmooring, anchoring/un-anchoring, recording/reporting, etc.) Hull-related (hull maintenance, patrol, cleaning, etc.) Cargo management (loading plan, cargo status management, cargo handling preparation work, cargo handling control, ship's attitude maintenance, etc.)
Engine department	Navigation (main engine operation, patrol (including trouble shooting), response to alarm, recording, regular maintenance/inspection, etc.) Port entry/departure-related (preparation work (inspection, operation check, changeover of fuel oil, starting stand-by generator, etc.), main engine load adjustment, lubricating oil adjustment during main engine slow down, fuel consumption minimization, seawater intake switching according to water depth , recording, main engine stopping work, etc.) Clean up

1.3 Level of Autonomy for "Ship" and "System"

Various discussions have also been held on the level of autonomous ship. Regarding the level of autonomy for a ship, interim

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definition (Table 2) is provided by IMO. In Japan, the phase of autonomous ship is listed in the roadmap for practical use of automatic operation ship announced by the MLIT (Table 3).

Regarding the level of autonomy for a system, the concept is shown in the guidelines issued by some classification societies (Table 4). The concept that the system will gradually and partially replace the decision-making process that has been carried out by crew is common to major classification societies.

Table 2　Degree of autonomy by IMO (MSC 100/20 / Add.1 Annex 2)

Degree one	Ship with automated processes and decision support
Degree two	Remotely controlled ship with seafarers on board
Degree three	Remotely controlled ship without seafarers on board
Degree four	Fully autonomous ship

Table 3　Phase of autonomous ship by the MLIT

Phase I	Ships utilizing IoT technology
Phase II	Ships that support the crew by remote maneuvering from land or action proposing function through AI etc., but the final decision is made by the crew
Phase III	Highly autonomous ships which the system can make the final decision for some tasks in place of the crew

Table 4　Level of autonomy for a system by classification societies [1-5)]

ABS	＜System Autonomy Levels＞ Level 1 Smart Level 2 Semi-Autonomous Level 3 Autonomous An autonomous system or function will be one where all four steps in the operational decision loop will be carried out by machines. The role of humans in such systems will be supervisory with the option to intervene and override the actions being carried out by the system.
BV	＜Level of autonomy＞ The level of autonomy should be defined to make a distinction between the role of the human and the role of the system among the various functions of the system. These functions are based on a four-stage model of human information processing and can be translated into equivalent system functions: a) information acquisition b) information analysis c) decision and action selection d) action implementation. The four functions can provide an initial categorization for types of tasks in which automation can support the human. Level 0 Human operated Level 1 Human directed Level 2 Human delegated Level 3 Human supervised Level 4 Fully autonomous
DNV	＜Levels of autonomy for navigation function＞ M: Manually operated function. DS: System decision supported function. DSE: System decision supported function with conditional system execution capabilities (human in the loop, required acknowledgement by human before execution).

	SC: Self controlled function (the system will execute the operation, but the human is able to override the action. Sometimes referred to as 'human on the loop'. A: Autonomous function (the system will execute the function, normally without the possibility for a human to intervene on the functional level). It is necessary to break the degree of autonomy further down. Below is a method that may be used to clarify which part of a function that is intended to be solved by a human and which to be solved by a system. Initially the control of a function can be divided into four main parts: - Detection - Analysis - Planning - Action
LR	＜Autonomy level (AL)＞ AL0) Manual AL1) On-board Decision Support AL2) On &Off-board Decision Support AL3)'Active' Human in the loop AL4) Human on the loop, Operator/ Supervisory AL5) Fully autonomous: Rarely supervised operation where decisions are entirely made and actioned by the system. AL6) Fully autonomous: Unsupervised operation where decisions are entirely made and actioned by the system during the mission.
NK	Combination of 1) to 3). 1) Scope of automation Level 0: Humans executes all subtasks Level I: Computer systems execute some decision-making subtasks Level II: Computer systems executes all subtasks 2) Scope of remote operation Level 0: Crew onboard execute all subtasks Level I: Some decision subtasks remotely executed Level II: All decision subtasks remotely executed 3) Fallback executor Level 0: Human executes Fallback Level I: Fallback execution is shared between humans and computer systems. Level II: Computer system execute fallback

Each Classification Societies has its own way of dividing the decision-making process, but ClassNK divides it into three categories: situation awareness, decision, and action, as shown in Fig. 1.

When considering the safety of an autonomous ship, it is important to sort out things such as which functions of the ship (maneuvering, propulsion, power management, cargo management, etc.), to what extent (part or all of the decision-making process), and who responds in the event of an emergency.

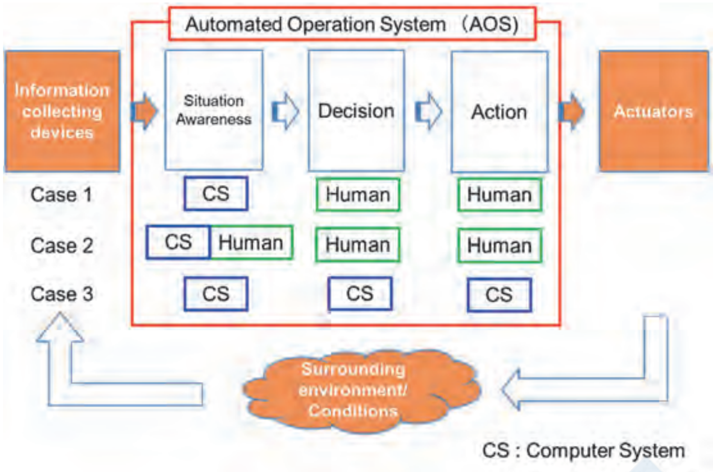

Figure 1　Conceptual diagram of Automated Operation System

1.4　Concept of Operation (ConOps)

In recent years, the term ConOps (Concept of Operation) has come to be often seen in documents related to autonomous ships. As far as the author has investigated, it seems to be a term used in system engineering, and it is described in ISO / IEC / IEEE 29148 (see Fig. 2). ConOps refers to a document that summarizes the concept and outline of system usage and operation, and it is positioned as an important document for eliciting stakeholder requirements and system requirements. Although system requirements tend to focus on the required capabilities and functions, it is possible to define requirements without omission (or few) by drawing a usage/operation scenario that covers the entire life cycle of the system.

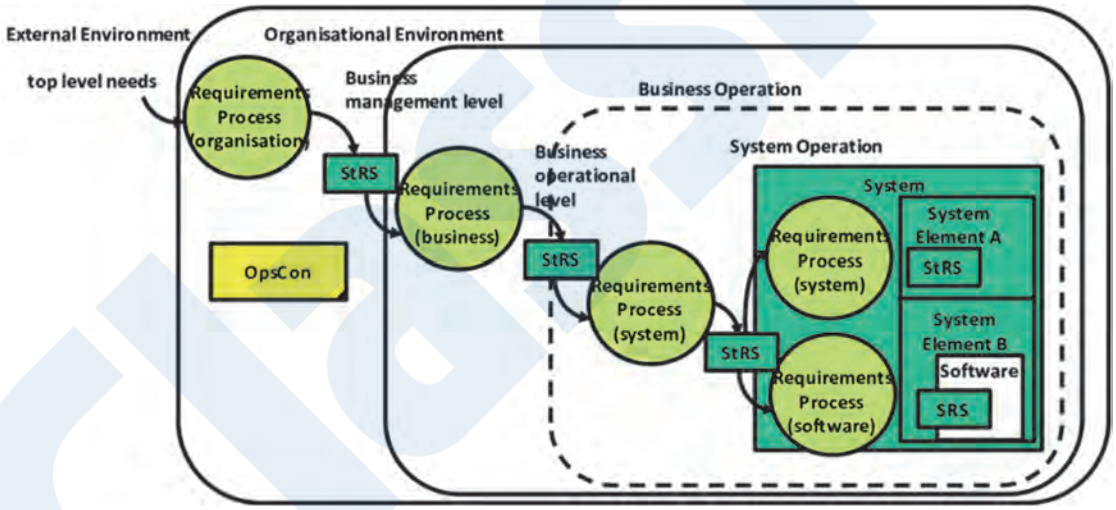

Figure 2　Example of requirement definition process flow and corresponding requirement specifications (Source: ISO / IEC / IEEE 29148)

In the case of autonomous ships, a highly complicated system will be installed, and it is difficult to set uniform requirements for such a large-scale system. This is because even if the systems have the same functions, the requirements and performance standards that should be specified are different depending on the conditions under which the system is operated. From this point of view, the approach of setting requirements after clarifying ConOps can be said to be an effective approach when verifying the safety of systems related to autonomous operations.

1.5　Technology Development

There are several ways to develop technologies related to autonomous ships. There are various approaches, for example, bringing in the latest technology such as AI, bringing in technology that has not been used in ships but has already been used in other industries, and combining existing technology that has already been used in ships in an unprecedented way so that it can realize new functions, and so on. Considering the nature of the target onboard task, it is being attempted to realize autonomous operation by appropriately selecting or combining two types of technologies, automation and remote control.

1.6 Rule Development

For implementation of the technology related to autonomous operation in society, the development of rules must be promoted in parallel to technology development.

At the IMO, autonomous ships have been taken up as an agenda item since MSC98 held in June 2017, and the framework and methodology for Regulatory Scoping Exercise (RSE) has been started. At MSC101 held in June 2019, interim guidelines for MASS(Maritime Autonomous Surface Ships) trials [6] (hereinafter referred to as IMO interim guidelines) were approved, and it summarizes the basic policies that should be taken into consideration when conducting trial operations of systems and infrastructure related to autonomous ships. At MSC103 held in May 2021, it was reported that RSE has been accomplished. In result of RSE, potential gaps between the current IMO instruments and requirements for MASS, and priorities for further work, were identified. In conclusion, it was agreed to consider a separate MASS instrument from existing IMO instruments.

In January 2020, ClassNK issued guidelines for automated/autonomous operation on ships (Ver. 1.0) (hereinafter referred to as NK guidelines) (see Fig. 3). The guidelines show the concept and certification procedure for automatic operation technology from the viewpoint of classification society.

Figure 3 Guidelines for automated/autonomous operation on ships (Ver. 1.0)

It is necessary to understand what kind of technology is currently being developed. It is important to correctly understand the “difference” from the conventional technology and share it with the parties concerned including the classification society from the conceptual design stage. Rather than uniformly defining normative requirements from the beginning, it is necessary to rationally evaluate autonomous technology while utilizing methods such as risk evaluation.

By following this process, the classification society can proceed with the development of rules, and the system owner can build a concrete usage image (business image). System suppliers and system integrators can also clarify the direction of development. In addition, by clarifying the procedure for certification of autonomous operation technology, it becomes easier for system suppliers, system integrators, and system owners to understand when and what they must do. It is expected that NK guidelines contribute to accelerate social implementation.

Further cooperation in the maritime industry including the classification society will become important.

2. SAFETY OF AUTONOMOUS SHIPS

2.1 Definition of Safety

It is necessary to clarify “what is safety”. For example, ISO / IEC GUIDE 51: 2014 defines safety as “no unacceptable risk”. Needless to say, “Zero risk (absolute safety)” is ideal, but it would be the definition as described above from a realistic point of view. Applying this definition of safety to ships, the means to eliminate “unacceptable risks” is the crew in the case of conventional ships, and the cooperation between system and crew in the case of autonomous ships.

The necessary capability for crew is specified in the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). It is necessary to discuss whether these capability requirements should be applied to the system as they are, but in an autonomous ship, if the system partially replaces the capability of crew, how the system achieves these capability requirements is an important point of view.

2.2 Functional Safety

Safety includes intrinsically safe and functional safety. Intrinsically safe means reducing or eliminating the cause of a machine's harm to humans and the environment. Functional safety means ensuring an acceptable level of safety by introducing functional devices (functions to ensure safety: safety functions).

Functional safety has been adopted in various industries, and there are functional safety standards such as IEC 62278 for railways and ISO 26262 for automobiles. As an example, ISO 26262, which is a functional safety standard for automobiles, aims for zero human damage based on the concept of functional safety. The background of the enactment is to fulfill accountability by visualizing the entire development work and to prepare evidence that can withstand the litigation.

Functional safety standards for ships do not yet exist, but the concept of functional safety is also helpful for autonomous ships.

2.3 Equivalency

When discussing the safety of autonomous ships, one approach is to compare it with the safety of conventional ships. The purpose of installing an advanced system on a ship is not only improving safety, but also improving convenience or economy. Therefore, it is not necessary to require more safety than conventional ships just because it is an autonomous ship.

Conventional ships are operated safely by crew (qualified persons who have received formal training), and this procedure has been agreed globally. The conventional ship can be said to be “in a state where the risk is minimized” by the crew.

In an autonomous ship, this “state in which the risk is minimized” will be realized by the autonomous technology (automation and/or remote control). In other words, it is necessary to confirm the difference between the conventional ship and the autonomous ship, and to confirm that the safety of the conventional ship is not impaired by the difference.

2.4 Safety in Normal Condition and Safety in Emergency Condition

It is necessary to consider safety separately for “normal condition” and “emergency condition”. In “normal condition”, the minimum requirements defined in advance must always be satisfied. On the other hand, in an “emergency condition”, the situation has been already below the predefined minimum requirements (safety requirements in normal condition), so it is important to “not make the situation worse”.

2.5 MRC and MRM

In the case of automated driving of automobiles, the term Minimum Risk Maneuver (MRM) is used. It refers to vehicle motion control up to the Minimum Risk Condition (MRC) (stopped state where the accident risk is sufficiently low) as a countermeasure when an event that does not allow safe driving occurs. On the other hand, in case of ships, it is difficult to uniformly define a state in which the risk of accidents in an emergency is sufficiently low (MRC in an emergency). Unlike automobiles, ships that are affected by waves and tides will drift if the main engine is stopped. Also, anchoring to stay in one place can rather endanger the condition of the vessel in some circumstances. It is necessary to take flexible measures in consideration of the surrounding conditions, the atmosphere, the abnormal mode that occurred on the ship, and so on. In the case of conventional ships, the crew appropriately decide actions to “do not make the situation worse” (MRM in automobiles) according to the situation, and this flexible responsiveness of the crew supports the safe operation of the ship.

It is technically very difficult for the system to be in charge of MRM in an emergency on an autonomous ship. Therefore, the crew will need to fallback for the time being. A fully autonomous ship will appear when the system can handle emergency automatically, or when the probability of occurrence can be approached to zero.

2.6 Risk Assessment

For autonomous ships, due consideration in various operational scenarios must be given to prevent predictable accidents. As a method for this purpose, risk assessment is effective. Some Classification Societies, including ClassNK, have already issued guidelines on autonomous ships, and risk assessment is emphasized in all of them. IMO Interim Guidelines [6)] and Guidelines issued by some flag states [7-9)] also specify the implementation of risk assessment. There is no doubt about the international trend of utilizing risk assessment to verify the safety of autonomous ships.

2.7 Basic Elements for Safety Evaluation

The NK guidelines state that it is important to clarify or consider the following eight basic elements for safety evaluation from the conceptual design stage. ClassNK will verify the safety of system for autonomous ships in combination of these elements rather than isolation.

(1) Target of autonomous operation on a ship
(2) Division of roles between machines and humans
(3) Prerequisite specification for system installation
(4) Operation Design Domain (ODD)
(5) Fallback
(6) Human Machine Interface (HMI)
(7) Cyber security
(8) Reliability of Computer Systems

Adding the above-mentioned concept of MRC and MRM to these elements gives an image as shown in Fig. 4. It is very important for safety evaluation to verify how define the ODD including geographical conditions, environmental conditions, presence of land support, etc., and under what circumstances the system is operated (ConOps), as well as how transfer tasks to crew (fallback) when the system cannot work appropriately due to deviation from the ODD.

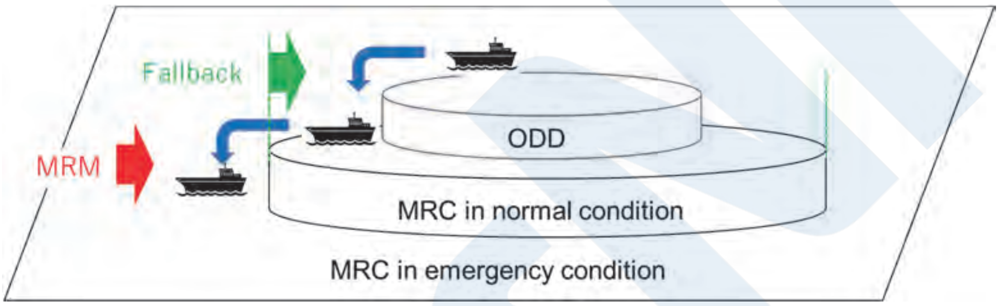

Figure 4 Relationship between ODD, Fallback, MRC, and MRM

2.8 Challenges

As mentioned, risk assessment is effective as a method for evaluating the safety of autonomous ships, but there are challenges. Since there are a wide variety of onboard operations and the magnitude of risk varies depending on the circumstances, which operations are autonomous, to what extent, and who (crew or system) responds at what timing in the event of an emergency, it is necessary to extract hazards from very multifaceted angles in risk assessment. In addition, countermeasures will be taken to mitigate the risk caused by the extracted hazards to an “acceptable level”, but it is difficult to quantify this “acceptable level”. For the time being, it is necessary to proceed with verification using whether or not it is “equivalent to a conventional ship” as an index, and to accumulate knowledge for quantification.

3. SYSTEM EXAMPLE FOR SHIP MANEUVERING

3.1 Target

Due to the wide variety of onboard operations on ships, discussions related to autonomous ships tend to diverge. Especially in conceptual level discussions, individual knowledge levels and term definitions are often inconsistent. To promote constructive discussions efficiently, it is necessary to give concrete examples as much as possible. It is important to form a common understanding and create a situation where each expert can bring their own specialties and have discussions.

In this paper, a virtual study was conducted on the system required for autonomy of ship maneuvering. The staffing of crew is based on the premise that they comply with the current rules, and unmanned ships are not assumed. Similar studies [10)] have also been conducted, and it is expected that these researches contribute to accelerate the formation of a common understanding in the industry.

3.2 An Example of System for Ship Maneuvering on an Autonomous Ship

Figure 5 shows an image of maneuvering operation on an autonomous ship. In this figure, the components of maneuvering task are divided into five modules, information collecting device, situation awareness, decision, action, and actuators. In the remote operation center, it is assumed that the remote operator would monitor, support, and/or control some modules other than actuators as needed.

(1) Information collecting device

In addition to existing sensors, it is assumed that a sensor that supports or replaces the lookout by the crew (hereinafter lookout sensor) will be installed. It seems difficult to develop a lookout sensor that is a perfect substitute for lookout by the crew, but if such a lookout sensor is developed, it is necessary to develop performance standards which can evaluate the equivalence with lookout by the crew, as well.

(2) Situation awareness

It is necessary to integrate the information obtained from the information collecting device, confirm the reliability of the information, and accurately grasp the situation in which the ship is placed.

By improving the reliability and integrity of information by sensor fusion technology, an information display device with a human-machine interface devised to make it easier for crew to understand, that can display the risk of collision with other ships and the risk of grounding, will be developed as well as the algorithms which can accurately analyze the state of the own ship from the given information.

(3) Decision

Quantitative indexes are necessary for computer system to decide whether to maintain the route/speed or move to avoidance action. In addition, when avoidance action is required, the function of planning an avoidance action is also required. It is assumed that a highly reliable automatic collision avoidance algorithm will be developed in consideration of these factors. It is believed that the autonomous operation will be introduced in stages, and it will be introduced from the style in which the crew approve what the system proposes. When the system operation results are accumulated and the reliability of the system algorithm is sufficiently confirmed, it will be possible to take action without human approval under the supervision of a crew.

Since it is related to the reliability and integrity of the situation awareness, it is considered that the crew onboard will be responsible for the decision in maneuvering of autonomous ship for the time being. If crew onboard and remote operators at remote operation center work together, authority and responsibilities for final decision are to be clarified center in advance.

(4) Action

In both cases that it is to maintain the route or to take avoidance action, calculations are made to control the ship along the designated route. Since HCS (Heading Control System) and TCS (Track Control System) already exist, it is conceivable that these technologies will be applied.

The required accuracy such as off-track width, etc. needs to be adjusted appropriately in consideration of the maneuverability of the own ship and the parameters used in the avoidance route planning of the decision module.

(5) Actuators

It is assumed that conventional devices will be used for the time being.

(6) Remote operation center

For the information collection module, it is assumed that the remote operation center will provide support such as updating the latest meteorological and ocean conditions, traffic information, and medium- to long-term voyage plans.

In situation awareness module, the work content in the remote operation center changes greatly depending on the comprehensiveness and timeliness of the information sent from the ship. For example, when a remote operator performs remote maneuvering (maneuvering a ship outside of sight), cognition including visual images is also required at the remote operation center, and cognitive quality almost equivalent to that on board is required. In addition, whether or not high-quality cognition can be stably reproduced depends on the communication environment. On the other hand, if the purpose is to monitor the condition of onboard equipment or evaluate the condition from information such as sensor data, the required communication environment is also relaxed.

In decision module, it is assumed that support such as action planning and advice to the crew onboard will be the main focus.

It is assumed that the module of action and actuators will not be supported.

When evaluating the safety of a ship maneuvering system, a two-step verification will be carried out. After confirming the

reliability of each of the above five modules, check the functions with these modules integrated.
Technological development continue and each module will be updated. In such a case, making it easier to take the difference is a great merit of proceeding with verification on a module-by-module basis.

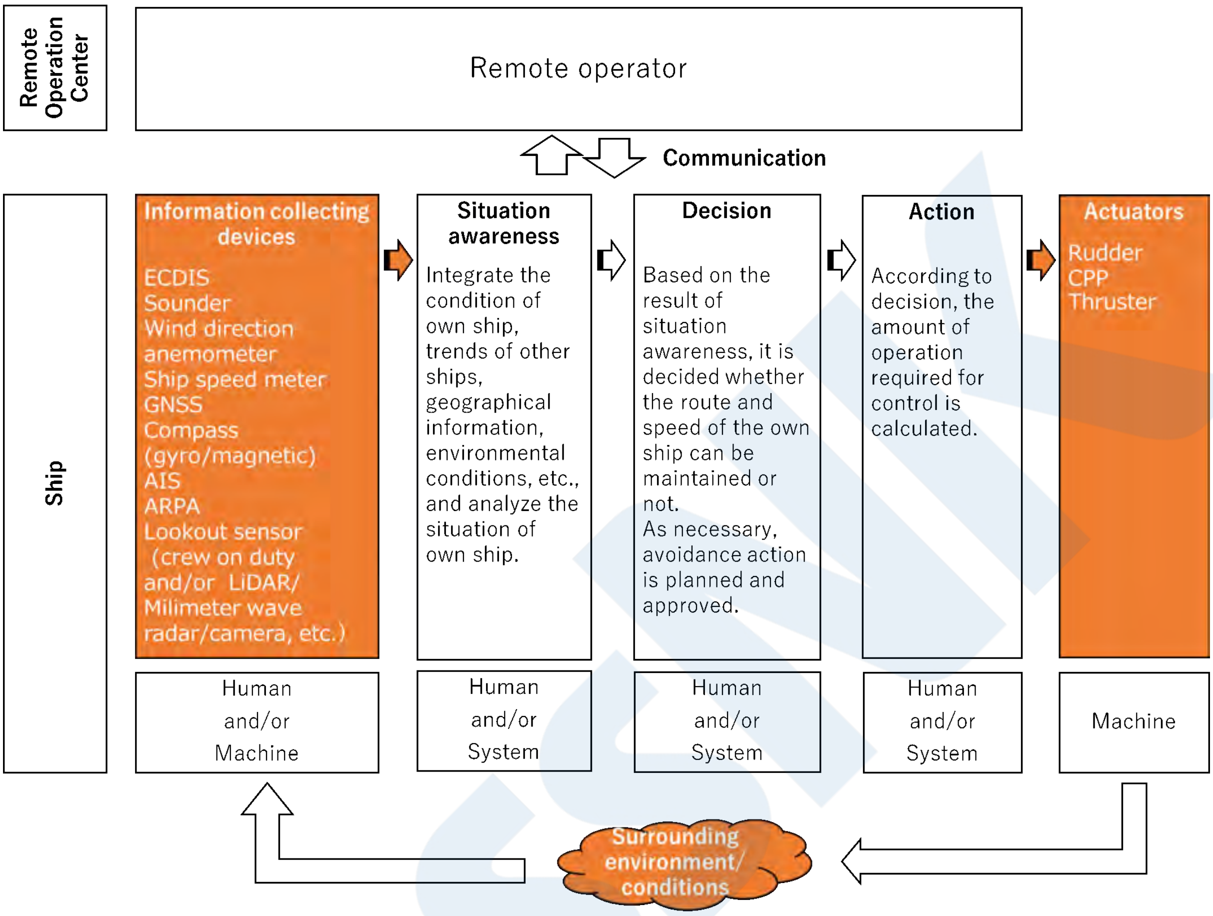

Figure 5 Image of maneuvering operation on an autonomous ship

4. INITIATIVES OF RESEARCH INSTITUTE OF CLASSNK

ClassNK is carrying out R&D on specific methods for conducting safety evaluations. Especially, methods of extracting hazards during risk assessment and computer simulation for quantitative evaluation are focused.

As mentioned above, since there are a wide variety of technologies related to automatic operation, the Society has narrowed down the target of autonomy to ship maneuvering operation, and detailed studies are being conducted. Based on the knowledge gained there, the verification study will be expanded to autonomy of other onboard operations.

4.1 Study for Comprehensive Hazard Extraction Method

In case of auto-driving cars, it seems that the idea is to prevent foreseeable accidents, and the same is true for autonomous ships. Hazard extraction is performed after considering under what circumstances, what task is automated, how much remote control is performed, and who (crew or system) responds at what timing in the event of an emergency. Then, the magnitude of those risks is estimated. For that purpose, it is necessary to accurately grasp where the difference in technology from the conventional ship exists. It is believed that the overall risk will be lower when comparing autonomous ships with conventional ships, but there is a possibility that new risks will arise that conventional ships did not have. For the time being, it will be important to properly identify such risks, and operate with an appropriate safety margin.

For that reason, the ClassNK guidelines describe eight basic elements for safety evaluation. Based on these basic elements, ClassNK is also researching ways to make it easier to extract hazards by organizing the functions of autonomous systems while considering the decision-making process. The findings obtained from the demonstration projects, etc. that ClassNK has been involved in are being organized in the format shown in Table 5. We are sorting out common requirements and special requirements by comparing and verifying multiple cases in a unified format.

In risk assessment of autonomous ships, it is important to verify hazards related to inter-system cooperation and cooperation between systems and humans, in addition to hazards focusing on equipment failures. From that point of view, ClassNK is proceeding with verification from the following viewpoints.

(1) Hazard that occurs when the system and human collaborate
(2) Hazard hidden in the decision-making process flow (Information collection device→Situation awareness→Decision→Action→Actuators)
(3) Validity verification of ODD
(4) Extraction of fallback occurrence scenarios
(5) Hazard that may occur when switching modes

The reliability of HMI, cyber security, and computer systems in individual modules will be verified when the detailed design is completed. As a verification method at that time, methods such as connection tests on actual machines and computer simulations might be more suitable than risk evaluation.

Table 5 Format for analysis of decision-making process flow based on basic elements for safety evaluation

Task	Mode	Prerequisite specification for system installation								ODD	Fallback
		Information collecting device (Input)	Situation awareness		Decision		Action		Actuators (Output)		
			Excuter	Place	Excuter	Place	Excuter	Place			
Ex)											
Maneuvering	Congested sea area	ECDIS Sounder Wind direction anemometer Ship speed meter GNSS Compass(gyro/ magnetic) AIS ARPA Lookout sensor	Support system + Crew	Ship	【Planning】 System + 【Approve】 Cres	Ship	System	Ship	Radder	Geographical conditions: Environmental condition: Other conditions:	Crew

4.2 Establishment of Quantitative Evaluation Method

It is difficult to achieve social implementation through risk assessment alone. As a classification society, it is necessary to set certain standards and ensure they are cleared. From such a perspective, ClassNK is paying particular attention to computer simulation. Figure 6 shows an image of the quantitative evaluation method currently under consideration.

To evaluate the safety of the developed ship maneuvering algorithm, it is necessary to verify whether or not it can appropriately respond to scenarios that lead to accidents. The combination of various other ship encounter patterns and disturbances will be comprehensively verified by fast-time simulation. In addition, conducting real-time simulations using a full-mission simulator to verify the timing of handing over tasks to crew in an emergency and the required HMI is also considered.

For quantitative evaluation of the simulation results, it is necessary to determine the evaluation index. Therefore, a method for quantitative evaluation of ship maneuvering [11-12] is being also developed in cooperation with captains who have rich experience. Study for scenarios for computer simulation and appropriate index for evaluating the simulation results are being steadily proceeded, and the study results will be summarized during this fiscal year.

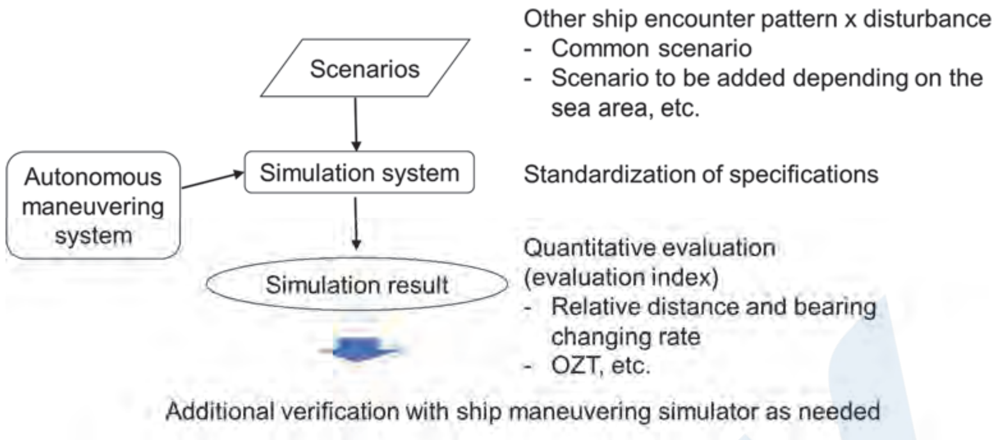

Figure 6 Quantitative evaluation method for ship maneuvering system

4.3 Establishing Requirements for Remote Control

There are three types of remote control technology for autonomous ships, monitoring, support (information provision, planning support, etc.), and control (direct operation of actuator, etc.). The requirements to be specified are different depending on the nature of the task to be carried out in the remote operation center.

It is also necessary to consider the characteristics peculiar to remote control. Specifically, it is necessary to sort out the requirements for the communication infrastructure, the equipment used in remote operation center, and the operators involved, etc. These are not complete with the ship alone. In the case of automation technology, it is necessary to pay attention to the part of cooperation between humans and machines onboard, but in the case of remote technology, it is necessary to pay attention to how and to what extent communication between crew onboard and remote operators is planned. It means important to clarify the ConOps.

In consideration of the characteristics peculiar to such remote technology, ClassNK is proceeding the study from the following three main viewpoints.

(1) Establishment of evaluation method for communication stability
(2) Clarification of requirements for remote control facilities
(3) Clarification of requirements for remote control workers

5. CONCLUSION

It is the role of the classification society to develop rational rules for autonomous ships. The Society has been steadily making preparations in cooperation with stakeholders, such as issuing guidelines in May 2018 and January 2020. In the future, the Society is going to continue to proceed with a solid sense of balance so that ClassNK can establish the necessary and sufficient safety requirements for autonomous ships without delaying technological development.

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Development of Simplified Formula for Froude-Krylov Force of 6-DOFs Acting on Monohull Ship

Sadaoki MATSUI*, Kyohei SHINOMOTO**, Kei SUGIMOTO**, Shinsaku ASHIDA***

1. INTRODUCTION

In ship design, highly accurate estimation of ship motion in waves is demanded from various viewpoints, including the safety and riding comfort of the crew, wave loads for hull structural design, added resistance in waves in propulsive performance, etc. Rational estimation of ship motion in waves is now possible by seakeeping analysis tools such as the strip method or 3D panel method, and these tools have been provided for practical use at design work sites. On the other hand, there is also high demand for estimation of ship motion by a simple method which does not rely on numerical analysis. For example, in estimation of wave loads for evaluation of structural strength, performing wave load analyses for individual ships would be a significant obstacle in terms of the workload required in hull structural design. Therefore, CSR (Common Structural Rules) [1], which is a set of rules for steel ships, provides a method for estimating wave loads by simplified formulae using the main parameters of the ship. For the same reason, the intact stability criteria (International Code on Intact Stability; IS Code) [2] established by the IMO requires evaluation of safety based on the effective wave slope coefficient and damping force in rolling motion obtained by a simplified estimation method.

Generally speaking, a tradeoff relationship exists between the “simplicity” of simplified estimation methods and their “estimation accuracy and range of applicability.” If a formula is developed by fitting to lots of the results of calculations, it is difficult to guarantee accuracy for targets that deviate from the used sample data. For example, the formulae for ship motion and acceleration provided in the current CSR [1] were derived by fitting to calculations for bulkers and oil tankers, and although the formulae are simple, they are not suitable to apply for untargeted ship types and sizes. Conversely, because the estimation formula for the effective wave slope coefficient provided in the IS Code [2] requires shape information for each transverse section of the hull, it is a strict method with high accuracy but lacks simplicity. In contrast to these two approaches, the authors believe that it is possible to satisfy both “simplicity” and “accuracy and applicability” by a process of identifying the dominant factors based on physical consideration, investigating their effects.

With this background, in the present research, the authors developed simplified formulae for the linear Froude-Krylov force based on a physical consideration to enable simple estimation of the ship motion in waves of a monohull ship of any arbitrary ship type and size. Although the work by Jensen et al. [3] is an example of past research for a similar purpose, that method was based on a formulation based on strip theory for a box-shaped ship with uniform dimensions of $L \times B \times d$, and the influence of the fineness of the ship geometry is considered by coefficient processing so as to fit several ships. In contrast, in the present research, we developed formulae that consider hull-form parameters of a ship such as the principal -particulars and fineness coefficients to enable application to all ship types from fine to blunt hull types. The estimation accuracy of the developed formulae was validated by calculation and comparison of the Froude-Krylov forces for various wave directions and wave lengths by a linear 3-dimensional seakeeping program using the actual hull-forms of 77 ships under 2 loading conditions (full load, ballast).

This paper is limited to the development of formulae for the Froude-Krylov force. However, because the Froude-Krylov force accounts for the main components of hydrodynamic forces that act on a ship, expressing those components by explicit formulae has a complete significance in itself. Its importance varies depending on the mode of motion, as the Froude-Krylov force is the principal component which becomes the leading term in the long wave length region [4] [5], while radiation and scattering hydrodynamic forces are also important in the wave length region where motion is large. In contrast to this, it is known that the Froude-Krylov force is particularly dominant for ship motion under roll and surge conditions. Where roll is concerned, because the scattering hydrodynamic force and the sway-induced radiation hydrodynamic force have a mutually-canceling effect,

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accurate estimation is possible by an equation of motion with one degree of freedom (DOF) using only the Froude-Krylov moment in the wave exciting force [6) 7)]. This concept has also been adopted in the IS Code [2)]. Surge can be estimated approximately from the Froude-Krylov force and hull weight because the fore and aft parts of ships are slender and elongated, and this calculation method has been adopted in many strip methods which do not consider the ship longitudinal component of the hull surface normal vector [8)]. The simplified formulae of the Froude-Krylov forces proposed in this paper are considered to be particularly effective for use in simplified estimations of these motions.

2. DEFINITIONS

2.1 Hull-Form Parameters Used in Formulae

Eight hull-form parameters are used in the formulae in this paper: the ship length L (length between perpendiculars, Lpp), breadth B, mean draft d, block coefficient C_b (=∇/LBd: where ∇ means displaced volume), waterplane area coefficient C_w (= Aw/LB: where Aw means the waterplane area), midship section area coefficient C_m, height of the center of gravity from keel KG and the longitudinal center of floatation using the center of gravity as the reference point x_f (= (longitudinal center of floatation LCF) – (longitudinal center of gravity LCG)). x_f is defined by Eq. (18) in the following. In this paper, the prismatic coefficient Cp (= C_b/C_m) and the vertical prismatic coefficient C_{vp} (= C_b/C_w) are used where appropriate. In addition, formulae were also developed for cases where the longitudinal metacentric height GM_L and the transverse metacentric height GM (defined by Eqs. (19) and (20) in the following) are used.

2.2 Coordinate System and Incident Wave

The definitions of the coordinate system and the directions of motions are shown in Fig. 1. The origins of the x, y, z coordinates are taken at the longitudinal center of gravity LCG, the centerline and the height of the waterline, respectively.

In this paper, the frequency response in regular waves was assumed based on linear theory and is expressed by the complex amplitude. That is, the amounts $a(t)$ of periodic variation are all handled by the complex number A defined by the following Eq. (1).

$$\begin{aligned} a(t) &= \Re[Ae^{i\omega_e t}] \\ &= \Re[A]\cos\omega_e t - \Im[A]\sin\omega_e t \\ &= |A|\cos(\omega_e t + \arg(A)) \end{aligned} \tag{1}$$

Where, ω_e is frequency of wave of encounter (frequency of encounter), and $\Re[A]$, $\Im[A]$, $|A|$, $\arg(A)$ are the real part, imaginary part, amplitude and argument of the complex number A, respectively.

The incident wave is defined as shown on the right in Fig. 1, and its velocity potential φ_0 is expressed as follows, assuming the instant when the crest of the wave reaches the position of the ship's center of gravity as the time reference (t = 0).

$$\phi_0 = \frac{ig\zeta_a}{\omega} e^{kz-ik(x\cos\beta+y\sin\beta)} \tag{2}$$

Where, g, ζ_a, ω, $k(=\omega^2/g)$, β are acceleration of gravity, and the wave amplitude, wave frequency, wave number and wave direction of the incident wave. In the following, the unit velocity potential shown below, which is nondimensionalized by $\omega/ig\zeta_a$, will be used.

$$\varphi_0 = e^{kz-ik(x\cos\beta+y\sin\beta)} \tag{3}$$

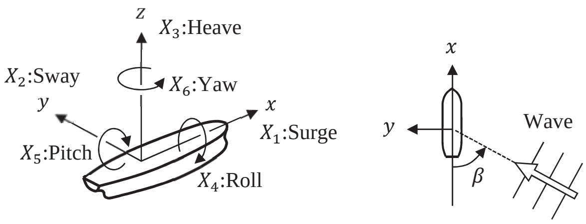


Figure 1 Definitions of coordinate system, motion and incident wave

2.3 Definition of Froude-Krylov Force and Asymptotic Value of Long Wave Length Region

The linear Froude-Krylov force is defined by the following equation as the integral of the velocity potential of the incident wave on the surface S_H of the ship's hull below the waterline.

$$E_i^{FK} = -\rho g \zeta_a \int_{S_H} \varphi_0 n_i \mathrm{d}S \qquad (i = 1\sim6) \tag{4}$$

$E_i^{FK} (i = 1 \text{ to } 6)$ are the Froude-Krylov forces in the surge, sway, heave, roll, pitch and yaw directions, respectively. When the basic flow field is approximated as a uniform flow, the definition in Eq. (4) holds independent of the ship's advance speed, and the influence of the advance speed is expressed only in the frequency of encounter ω_e. In Eq. (4), ρ is the density of seawater, and n_i $(i = 1 \text{ to } 6)$ represents the extension of the outward-facing unit normal vector $\{n_x, n_y, n_z\}^{\mathrm{T}}$ of the hull surface to 6 degrees of freedom (around the center of gravity) as defined by the following Eq. (5).

$$n_i = \begin{cases} n_x & (i = 1) \\ n_y & (i = 2) \\ n_z & (i = 3) \\ y n_z - (z - z_G) n_y & (i = 4) \\ (z - z_G) n_x - x n_z & (i = 5) \\ x n_y - y n_x & (i = 6) \end{cases} \tag{5}$$

Where, z_G is the z coordinate of the center of gravity (z_G = KG – d). In addition, the Froude-Krylov force in the surge, sway, heave and roll directions acting on a transverse section of a unit thickness (hereinafter referred to as "section Froude-Krylov force") is defined as shown by the following equation as the integral on the outer periphery $C_H(x)$ of the transverse section of the hull.

$$f_i^{FK}(x) = -\rho g \zeta_a \int_{C_H(x)} \varphi_0 n_i \mathrm{d}l \qquad (i = 1\sim4) \tag{6}$$

At this time, E_i^{FK} is expressed as follows using $f_i^{FK}(x)$.

$$E_i^{FK} = \begin{cases} \int_{x_A}^{x_F} f_i^{FK}(x)\mathrm{d}x & (i = 1\sim4) \\ \int_{x_A}^{x_F} -x f_3^{FK}(x)\mathrm{d}x & (i = 5) \\ \int_{x_A}^{x_F} x f_2^{FK}(x)\mathrm{d}x & (i = 6) \end{cases} \tag{7}$$

Where, x_A, x_F are the x coordinates of A.P. and F.P., respectively. In E_5^{FK}, E_6^{FK} of Eq. (7), the influence of the terms caused by n_x is considered to be negligibly small.

In the following, the Froude-Krylov force is nondimensionalized as follows, where the nondimensionalized quantity is indicated by an overbar.

$$\bar{E}_i^{FK} = \frac{E_i^{FK}}{\rho g \zeta_a L B \varepsilon_i} \quad (i = 1 \sim 6) \tag{8}$$

$$\bar{f}_i^{FK}(x) = \frac{f_i^{FK}(x)}{\rho g \zeta_a B \varepsilon_i} \quad (i = 2 \sim 4) \tag{9}$$

Here, ε_i is the representative length, which is defined as follows:

$$\varepsilon_i = \begin{cases} 1 & (i = 1 \sim 3) \\ B & (i = 4) \\ L & (i = 5,6) \end{cases} \tag{10}$$

Similarly, $\bar{x}$ obtained by nondimensionalizing x by L and $\bar{y}, \bar{z}$ obtained by nondimensionalizing y and z by B are used in the positional variables.

It is known that the asymptotic value of the Froude-Krylov force in the long wave length region corresponds to restoring force, and the consistency between the two influences the asymptotic value of motion [4]. Here, the exact value of the Froude-Krylov force will be presented in order to evaluate the asymptotic value in the long wave length region calculated by the simplified formulae. The following expressions are obtained by substituting the velocity potential of the incident wave shown in Eq. (3) into Eq. (4) and performing a Maclaurin expansion for k, and applying Gauss's divergence theorem to a scalar field (hereinafter referred to as the Gauss gradient theorem) .

$$\bar{E}_1^{FK} = i\bar{k}_l \frac{dC_b}{L} + O(k^2) \tag{11}$$

$$\bar{E}_3^{FK} = C_w - i\bar{k}_l \bar{x}_f C_w - kdC_b + O(k^2) \tag{12}$$

$$\bar{E}_5^{FK} = i\bar{k}_l \frac{dC_b}{L^2} \mathrm{GM_L} - \bar{x}_f C_w + O(k^2) \tag{13}$$

$$\bar{E}_2^{FK} = i\bar{k}_w \frac{dC_b}{B} + O(k^2) \tag{14}$$

$$\bar{E}_6^{FK} = \frac{\bar{k}_l \bar{k}_w}{L^3 B^2} \int_{V_H} (x^2 - y^2) \mathrm{d}V + O(k^3) \tag{15}$$

$$\bar{E}_4^{FK} = -i\bar{k}_w \frac{dC_b}{B^2} \mathrm{GM} + O(k^2) \tag{16}$$

Where, $O(k^n)$ is Landau's symbol, V_H is the displacement region and $\bar{k}_l, \bar{k}_w$ are the nondimensional wave numbers in the ship longitudinal and transverse directions, defined respectively as follows:

$$\bar{k}_l = kL\cos\beta \, , \bar{k}_w = kB\sin\beta \tag{17}$$

In the deformation of Eqs. (12) and (13), the following definition of the longitudinal center of floatation LCF is used.

$$\bar{x}_f = \frac{1}{C_w}\int_{\bar{x}_A}^{\bar{x}_F} \bar{x}\bar{B}_w(\bar{x})\mathrm{d}\bar{x} \tag{18}$$

Where, $\bar{B}_w(\bar{x})$ is a value obtained by dividing the waterline breadth $B_w(\bar{x})$ by B. $\mathrm{GM_L}$ on the right side of Eq. (13) is the longitudinal metacentric height (defined here as around the center of gravity) and GM on the right side of Eq. (16) is the transverse metacentric height. $\mathrm{GM_L}$ and GM are expressed as follows using the height of the center of buoyancy z_B and the height of the center of gravity z_G, respectively.

$$\mathrm{GM_L} = \underline{\frac{L^2}{dC_b}\int_{\bar{x}_A}^{\bar{x}_F}} \bar{x}^2\bar{B}_w\mathrm{d}\bar{x} + z_B - z_G \tag{19}$$

$$\mathrm{GM} \quad = \underline{\frac{B^2}{dC_b}\int_{\bar{x}_A}^{\bar{x}_F}\frac{\{\bar{B}_w(\bar{x})\}^3}{12}}\mathrm{d}\bar{x} + z_B - z_G \tag{20}$$

The underlined parts on the right side of Eqs. (19) and (20) are the longitudinal metacentric radius $\mathrm{BM_L}$ and the transverse metacentric radius BM, respectively.

The correspondence between the asymptotic value of the Froude-Krylov force in the long wave length region and restoring force can be confirmed from Eqs. (12) to (16). The first term on the right side of Eq. (12) corresponds to the nondimensional restoring force coefficient of heave, the first term on the right side of Eq. (13), $\mathrm{GM_L} \times dC_b/L^2$, corresponds to the nondimensional restoring force coefficient of pitch, the second term on the right sides of Eqs. (12) and (13), $-\bar{x}_f C_w$, corresponds to the nondimensional restoring force coefficient of coupled heave-pitch motion and the first term on the right side of Eq. (16), $\mathrm{GM} \times dC_b/B^2$, corresponds to the nondimensional restoring force coefficient of roll.

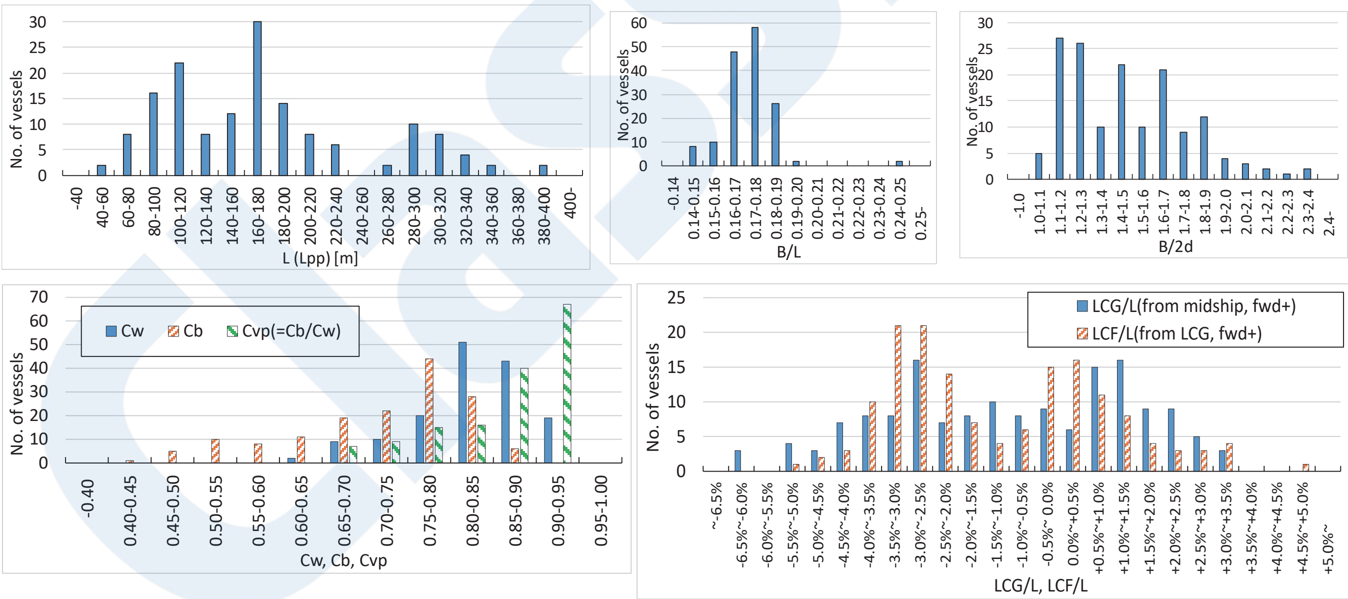


Figure 2　Histogram of hull-form parameters of target ships.

2.4　Numerical Calculation for Verification of Accuracy of Formulae

To verify the accuracy of the proposed formulae, calculations were performed by a linear 3-dimensional seakeeping program [9] developed by ClassNK, using 77 actually-existing ships under 2 loading conditions (full load and ballast condition). This program is based on a uniform flow approximation and calculates the Froude-Krylov force from the hull surface panels below the waterline by integral shown in Eq. (4). Because the targets here are general merchant ships, the area below the waterline is limited to bilateral symmetry and a monohull structure. However, a number of ship types were examined in this study, including bulk carriers, oil tankers, ore carriers, general cargo carriers, LNG carriers, LPG carriers, container ships, wood chip carriers, car carriers, RO-RO (roll-on/roll-off) ships, refrigerated cargo carriers (reefers) and cement carriers, and covered a wide range of L, C_w, C_b, B/L and $B/2d$, as shown in Fig. 2.

The wave conditions used in the comparison with the formulae in this paper included wave directions from β = 90° (beam sea) to 180° (head sea) in increments of 30°. For the wave length, wave length/ship length ratios λ/L of 0.5, 0.7, 1.0 and 1.5 were assumed. Where roll is concerned, estimation for a longer wave length region is important in some cases, but a numerical comparison was not carried out here because the asymptotic value for long wave lengths is evaluated separately by mathematical formulae. As mentioned above, the wave directions are limited to β = 90° to 180°. However, because the real part and imaginary part of the Froude-Krylov force acting on a bilaterally-symmetrical ship are symmetrical or antisymmetrial with respect to the wave direction, this range is neither excessive nor inadequate for verification of the real and imaginary parts. Here, it should also be noted that the Froude-Krylov force does not depend on the ship speed because the calculations are based on Eq. (4).

3. DEVELOPMENT OF SIMPLIFIED FORMULAE FOR FROUDE-KRYLOV FORCE

3.1 Basic Policy of Development

Because the Froude-Krylov force is the integral of the ship surface for a known scalar field, the key to the development of simplified formulae is “how to approximate the ship hull-form.” Since the purpose of this research is to express the Froude-Krylov force by an elementary function in which the variables are limited to only the main ship parameters and wave conditions, ship hull-form is approximated by a function that can be integrated analytically so that it is determined uniquely by the main ship parameters. As described detailly in the following sections, different hull-forms were selected for each mode of motion so that the formulae are simple and rational as the evaluation of the integrated value. In particular, the hull-form is decided with care so that the asymptotic value in the long wave length region either coincides with or is a good approximation of the result given by the exact equation shown in section 2.3. Furthermore, for the ship surface integral, the section Froude-Krylov force $\bar{f}_i^{FK}(\bar{x})$ is defined and is then integrated in the ship longitudinal direction, and the integrand is simplified appropriately in this process. For example, the Smith correction factor ($e^{-kd'(\bar{x})}$; where $d'(\bar{x})$ is the section draft) appears in the section Froude-Krylov force, but because integration is difficult or impossible when treating its longitudinal distribution, the integrand is simplified by replacing the section draft $d'(\bar{x})$ with the constant d_e (hereinafter referred to as “equivalent draft”) so that the integrals are equivalent.

3.2 Surge

As the point of departure of simplified methods for calculating $\bar{E}_1^{FK}$, the following expression, in which the Gauss gradient theorem is applied to Eq. (4), is often used.

$$\begin{aligned}\bar{E}_1^{FK} &= -\frac{1}{LB}\int_{V_H}\frac{\partial\varphi_0}{\partial x}\mathrm{d}V \\ &= i\bar{k}_l\int_{\bar{x}_A}^{\bar{x}_F} e^{-i\bar{k}_l\bar{x}}\left\{\int_{A_H(\bar{x})} e^{kz-iky\sin\beta}\frac{\mathrm{d}y\mathrm{d}z}{LB}\right\}\mathrm{d}\bar{x}\end{aligned} \tag{21}$$

Where, $A_H(\bar{x})$ is the transverse section below the waterline. $\bar{E}_1^{FK}$ is normally calculated based on Eq. (21) in strip method programs, which do not use n_x in calculations of hydrodynamic forces. The integral on $A_H(\bar{x})$ is solved by direct integration, or solved more simply by selecting a represented point of the wave particle velocity of the incident wave [8) 10)]. Here, $\bar{E}_1^{FK}$ is obtained analytically after approximating the section as a rectangle. Assuming the section geometry as rectangle with breadth $B'(\bar{x})$ and depth $d'(\bar{x})$, the integral on $A_H(\bar{x})$ can be expressed as follows:

$$\int_{A_H(\bar{x})} e^{kz-iky\sin\beta}\frac{\mathrm{d}y\mathrm{d}z}{LB} = \frac{1-e^{-kd'(\bar{x})}}{kL}\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w\bar{B}'(\bar{x})}{2} \tag{22}$$

Where, $\bar{B}'(\bar{x}) = B'(\bar{x})/B$. Substituting Eq. (22) into Eq. (21), $\bar{E}_1^{FK}$ is approximated as shown in Eq. (23).

$$\bar{E}_1^{FK} \cong i(1 - e^{-kd_e})\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right)\frac{\bar{k}_l}{kL}\int_{\bar{x}_A}^{\bar{x}_F} e^{-i\bar{k}_l\bar{x}}\bar{B}'(\bar{x})\mathrm{d}\bar{x} \tag{23}$$

In order to simplify the integral in the approximation in Eq. (23), the following approximation is assumed:

$$\sin\frac{\bar{k}_w\bar{B}'(\bar{x})}{2} \cong \bar{B}'(\bar{x})\sin\frac{\bar{k}_w}{2} \tag{24}$$

Furthermore, the draft $d'(x)$ in the Smith correction factor $e^{-kd'}$ is replaced with the equivalent draft d_e and removed from the integrand. Here, since it is considered possible to approximate the projected plane of the ship's shape below the waterline on the *y-z* plane as the rectangle $B \times dC_m$, it is assumed that $d_e = dC_m$. The distribution of $\bar{B}'(\bar{x})$ is assumed by a trapezoidal distribution of an area C_p with symmetry in the longitudinal direction, centering on the longitudinal center of buoyancy LCB.

$$\bar{B}'(\bar{x}) = \begin{cases} 1 & \text{for} \quad |\bar{x}| \le C_p - 0.5 \\ \dfrac{0.5 - |\bar{x}|}{1 - C_p} & \text{for} \quad C_p - 0.5 < |\bar{x}| \le 0.5 \end{cases} \tag{25}$$

The area of $\bar{B}'(\bar{x})$ is set to C_p in order to the nondimensional displacement is correspond to C_b (= C_pC_m). Substituting the above into Eq. (23), the following proposed formula is obtained.

$$\bar{E}_1^{FK} = i(1 - e^{-kdC_m})\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right)\left(\frac{2}{kL}\sin\frac{C_p\bar{k}_l}{2}\right)\left\{\frac{2}{(1 - C_p)\bar{k}_l}\sin\frac{(1 - C_p)\bar{k}_l}{2}\right\} \tag{26}$$

If the proposed formula shown in Eq. (26) is expanded for k, agreement of the asymptotic value in its long wave length region with the exact value given by Eq. (11) can be confirmed.

Figure 3 shows the comparison of $\bar{E}_1^{FK}$ by the developed formula shown in Eq. (26) and the numerical calculations for the actual ships shown in section 2.4. From Fig. 3, it can be understood that $\Im[\bar{E}_1^{FK}]$ has satisfactory accuracy for all ships and wave conditions. Regarding $\Re[\bar{E}_1^{FK}]$, in the calculations, this value becomes 0 by symmetric domain integration of odd functions because a anterior-posterior symmetric hull-form was assumed. In comparison with this, the value for the actual ships is at most about $\Re[\bar{E}_1^{FK}]$ = 0.02, confirming that the influence of the anterior-posterior asymmetry of the hull-form can be neglected.

Since the midship section area coefficient of almost all general merchant ships is in the range of $C_m > 0.96$, there is virtually no reduction in accuracy in many cases even if $C_m = 1$ is assumed in the calculation. However, if $\bar{B}'(\bar{x})$ is not considered as trapezoidal as in Eq. (25), but is approximated by a rectangular distribution of the area C_p, $\bar{E}_1^{FK}$ is represented by an equation which does not contain the expression shown in the curly brackets ({}) on the right side of Eq. (26), and in this case, estimation accuracy decreased remarkably in the short wave length region. Because n_x has a value mainly in the vicinity of the ship bow and stern, the importance of the approximation of the shapes of the bow and stern is higher than that of other hydrodynamic forces. Therefore, a highly accurate formula was obtained by assuming that the distribution of breadth in the ship longitudinal direction is a trapezoid close to that of the actual hull-form (see Table 1).

3.3 Heave and Pitch

When the transverse sectional geometry of the hull is considered to be a rectangle with breadth $B'(\bar{x})$ and depth $d'(\bar{x})$, the section Froude-Krylov force in the *z* direction $\bar{f}_3^{FK}(\bar{x})$ is expressed by the following Eq. (27):

$$\bar{f}_3^{FK}(\bar{x}) = \left\{\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w\bar{B}'(\bar{x})}{2}\right\}e^{-kd'(\bar{x}) - i\bar{k}_l\bar{x}} \tag{27}$$

By substituting Eq. (27) into Eq. (7), performing an approximation of Eq. (24), and removing the Smith correction factor from the integrant by using the equivalent draft d_e, $\bar{E}_3^{FK}$ and $\bar{E}_5^{FK}$ can be expressed as follows:

$$\bar{E}_3^{FK} \cong e^{-kd_e}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right)\int_{\bar{x}_A}^{\bar{x}_F} e^{-i\bar{k}_l\bar{x}}\bar{B}'(\bar{x})\mathrm{d}\bar{x} \tag{28}$$

$$\bar{E}_5^{FK} \cong e^{-kd_e}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right)\int_{\bar{x}_A}^{\bar{x}_F} -\bar{x}e^{-i\bar{k}_l\bar{x}}\bar{B}'(\bar{x})\mathrm{d}\bar{x} \tag{29}$$

Here, the equivalent draft d_e is assumed as average draft, i.e. $d_e = dC_{vp}$. Since $\bar{E}_3^{FK}$ and $\bar{E}_5^{FK}$ are integrals with respect to n_z, it is inferred that they are deeply related the shape of the projection plane of the hull-form in the z direction, that is, the shape of the waterline plane. Based on this idea, $\bar{B}'(\bar{x})$ is considered to be equivalent to the waterline breadth $\bar{B}_w(\bar{x})$. Assuming a rectangular distribution of the area C_w with its center at LCG,

$$\bar{B}'(\bar{x}) = \begin{cases} 1 & \text{for} \quad |\bar{x}-\bar{x}_f| \le C_w/2 \\ 0 & \text{otherwise} \end{cases} \tag{30}$$

In case the above is used, the integrals of Eqs. (28) and (29) are as follows:

$$\int_{\bar{x}_A}^{\bar{x}_F} e^{-i\bar{k}_l\bar{x}}\bar{B}'(\bar{x})\mathrm{d}\bar{x} = e^{-i\bar{k}_l\bar{x}_f}\left(\frac{2}{\bar{k}_l}\sin\frac{C_w\bar{k}_l}{2}\right) \tag{31}$$

$$\int_{\bar{x}_A}^{\bar{x}_F} -\bar{x}e^{-i\bar{k}_l\bar{x}}\bar{B}'(\bar{x})\mathrm{d}\bar{x} = ie^{-i\bar{k}_l\bar{x}_f}\frac{1}{\bar{k}_l}\left\{\left(\frac{2}{\bar{k}_l}+2i\bar{x}_f\right)\sin\frac{C_w\bar{k}_l}{2} - C_w\cos\frac{C_w\bar{k}_l}{2}\right\} \tag{32}$$

The expression $e^{-i\bar{k}_l\bar{x}_f}$ on the right side of Eqs. (31) and (32) is the phase difference due to the fact that the center of action of the Froude-Krylov force is the LCF, while the reference phase of the incident wave is defined by the center gravity of the ship's hull. On the other hand, the $\bar{x}_f$ in the parentheses that can be seen on the right side of Eq. (32) is the lever of the center of action of the Froude-Krylov force and center of gravity owing to the fact that $\bar{E}_5^{FK}$ is defined as the moment around the center of gravity.

The above-mentioned equations are derived as a result of regarding the hull as a "box-shaped vessel with dimensions of $LC_w \times B \times dC_{vp}$ with its center at LCF." This approximation seems reasonable in the case of beam sea because the incident wave profile is uniform in the ship's longitudinal direction, i.e., $e^{-i\bar{k}_l\bar{x}} = 1$. However, in the case of head sea or following sea, the wave profile $e^{-i\bar{k}_l\bar{x}}$ changes in the longitudinal direction in the short wave length region and it is not reasonable to approximate the hull-form as a box-shape. In order to water plane in the short wave length region of longitudinal waves and the influence of the fineness of the ship under waterline without sacrificing the simplicity of the formula, $\bar{k}_l$ in the equation is replaced with the following $\bar{k}_l'$:

$$\bar{k}_l' = C_b^{-0.15}\bar{k}_l \tag{33}$$

This correction was applied to the ship longitudinal nondimensional wave number $\bar{k}_l$ to change the value under a condition of longitudinal waves in the short wave length region, and C_b was used in the correction to correct both fineness at the water plane (C_w) and fineness below the water plane (C_{vp}) by $Cb = C_wC_{vp}$. The exponent –0.15 was decided to obtain high agreement, based on the results for the actual ships.

From the foregoing discussion, the following equations are proposed as the simplified formulae of the Froude-Krylov forces for heave and pitch.

$$\bar{E}_3^{FK} = e^{-i\bar{k}_l\bar{x}_f - kdC_{vp}}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right)\left(\frac{2}{\bar{k}_l'}\sin\frac{C_w\bar{k}_l'}{2}\right) \tag{34}$$

$$\bar{E}_5^{FK} = ie^{-i\bar{k}_l\bar{x}_f - kdC_{vp}}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right)\frac{1}{\bar{k}_l'}\left\{\left(\frac{2}{\bar{k}_l'} + 2i\bar{x}_f\right)\sin\frac{C_w\bar{k}_l'}{2} - C_w\cos\frac{C_w\bar{k}_l'}{2}\right\} \tag{35}$$

In these formulae, $\bar{k}_l$ is used instead of $\bar{k}_l'$ is used in $e^{-i\bar{k}_l\bar{x}_f}$. This is based on the consideration that $\bar{E}_3^{FK}$ should achieve its maximum (or minimum) value at the instant when the crest (or trough) of the incident wave reaches the position of the LCF.

The comparison of the results of the developed formulae shown in (34) and (35) and the values obtained by the numerical calculations are shown in Fig. 4 and Fig. 5, and confirm that the formulae have satisfactory practical accuracy for all ship types and wave conditions. A good correlation can also be seen for $\Im[\bar{E}_3^{FK}]$ and $\Re[\bar{E}_5^{FK}]$, which are caused by the anterior-posterior asymmetry of the hull-form. This means that it is appropriate to regard the center of action of Froude-Krylov force in the z direction as being located at the LCF.

Regarding the amplitude in Eqs. (34) and (35), because Fig. 2 showed that the value of $\bar{x}_f$ is small, being about ±0.05, the terms for the squares of $\bar{x}_f$ are neglected, and the expressions are rewritten as shown below.

$$|\bar{E}_3^{FK}| = e^{-kdC_{vp}}\left|\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right|\left|\frac{2}{\bar{k}_l'}\sin\frac{C_w\bar{k}_l'}{2}\right| \tag{36}$$

$$|\bar{E}_5^{FK}| = e^{-kdC_{vp}}\left|\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right|\left|\frac{1}{\bar{k}_l'}\left(\frac{2}{\bar{k}_l'}\sin\frac{C_w\bar{k}_l'}{2} - C_w\cos\frac{C_w\bar{k}_l'}{2}\right)\right| \tag{37}$$

In other words, $\bar{x}_f$ is mainly used in phase calculations, and its influence on amplitude can be neglected. In the above equations, agreement with the formulae according to Jensen et al. can be confirmed if $\bar{k}_w = 0$ and $C_w = C_b = 1$ are assumed. Although the complexity of the numerical expressions of the proposed formulae is virtually unchanged from that of Jensen's formulae, these are higher-order formulae from the viewpoint that the effects of the ship hull-form parameters C_b and C_w are given proper consideration, and phase information can be clearly obtained by $\bar{x}_f$.

Agreement of the asymptotic value of the proposed formula (34) for heave with the exact equation (12) can be confirmed. However, the asymptotic value of formula (35) for pitch in the long wave length region is as follows:

$$\bar{E}_5^{FK} \sim i\bar{k}_l'\frac{C_w^3}{12} - \bar{x}_f C_w \qquad \text{as } k \to 0 \tag{38}$$

Comparing the right side of (38) with the exact equation (13), it can be understood that the quantity which is equivalent to the nondimensional restoring force coefficient of pitch, $dC_b/L^2 \times \mathrm{GM_L}$, corresponds to the expression shown in (39).

$$\frac{dC_b}{L^2}\mathrm{GM_L} \leftrightarrow C_b^{-0.15}\frac{C_w^3}{12} \tag{39}$$

The right side of (39) is an expression which was obtained by multiplying the nondimensional restoring force coefficient of pitch $C_w^3/12$ when $\bar{B}_w(\bar{x})$ is approximated by a rectangular distribution (right side of Eq. (30)) by the correction factor $C_b^{-0.15}$. In spite of the fact that this expression is different from the left side of Eq. (39), it is not a poor approximation, and as can be confirmed from Fig. 5, its accuracy presents no problems for practical application in the long wave length region. Although we also studied approximation of $\bar{B}'(\bar{x})$ by a trapezoidal distribution, rather than by a rectangular distribution as in Eq. (30), there was no large improvement in accuracy that would justify the increased complexity of the formula. As a result, formulae (34) and (35) in which an approximation by a rectangular distribution was corrected by (33), were adopted as the proposed formulae in this research, as these formulae provide both simplicity and accuracy.

3.4 Sway and Yaw

When the transverse section geometry of the hull is considered as a rectangle with breadth $B'(\bar{x})$ and depth $d'(\bar{x})$, the section Froude-Krylov force in the *y* direction $\bar{f}_2^{FK}(\bar{x})$ is as follows:

$$\bar{f}_2^{FK}(\bar{x}) = i\{1 - e^{-kd'(\bar{x})}\}\left\{\frac{2}{KB}\sin\frac{\bar{k}_w \bar{B}'(\bar{x})}{2}\right\} e^{-i\bar{k}_l\bar{x}} \tag{40}$$

By substituting Eq. (40) into Eq. (7), performing an approximation of Eq. (24) and removing the Smith correction factor from the integrant by using the equivalent draft d_e, $\bar{E}_2^{FK}$ and $\bar{E}_6^{FK}$ are expressed as shown below.

$$\bar{E}_2^{FK} \cong i(1 - e^{-kd_e})\left(\frac{2}{KB}\sin\frac{\bar{k}_w}{2}\right)\int_{\bar{x}_A}^{\bar{x}_F} e^{-i\bar{k}_l\bar{x}}\bar{B}'(\bar{x})\mathrm{d}\bar{x} \tag{41}$$

$$\bar{E}_6^{FK} \cong i(1 - e^{-kd_e})\left(\frac{2}{KB}\sin\frac{\bar{k}_w}{2}\right)\int_{\bar{x}_A}^{\bar{x}_F} \bar{x}e^{-i\bar{k}_l\bar{x}}\bar{B}'(\bar{x})\mathrm{d}\bar{x} \tag{42}$$

Although the definitional equation of $\bar{f}_2^{FK}(\bar{x})$ shown in Eq. (6) is based on the surface integral, it can be replaced by the surface integral on the transverse section of φ_0 by applying the Gauss gradient theorem to that equation. Based on this fact, the equivalent draft is approximated as $d_e = dC_{vp}$, considering the influence of thinness below the waterline. However, for $\bar{E}_6^{FK}$, this is given as $d_e = dC^2_{vp}$ considering the asymptotic value in the long wave length region, as described at the end of this section. The breadth $\bar{B}'(\bar{x})$ is assumed to be a rectangular distribution of the area C_w with LCB as its center:

$$\bar{B}'(\bar{x}) = \begin{cases} 1 & \text{for} \quad |\bar{x}| \le C_w/2 \\ 0 & \text{otherwise} \end{cases} \tag{43}$$

Finally, the following simplified formulae are obtained by substituting Eq. (43) into Eqs. (41) and (42).

$$\bar{E}_2^{FK} = i(1 - e^{-kdC_{vp}})\left(\frac{2}{kB}\sin\frac{\bar{k}_w}{2}\right)\left(\frac{2}{\bar{k}_l}\sin\frac{C_w\bar{k}_l}{2}\right) \tag{44}$$

$$\bar{E}_6^{FK} = \left(1 - e^{-kdC_{vp}^2}\right)\left(\frac{2}{kB}\sin\frac{\bar{k}_w}{2}\right)\frac{1}{\bar{k}_l}\left(\frac{2}{\bar{k}_l}\sin\frac{C_w\bar{k}_l}{2} - C_w\cos\frac{C_w\bar{k}_l}{2}\right) \tag{45}$$

The comparison of the results by the developed formulae shown as Eq. (44) and Eq. (45) with the values obtained by the numerical calculations are shown in Fig. 6 and Fig. 7, respectively. It can be understood that the proposed formulae have satisfactory accuracy for all ship types and wave conditions. $\Re[\bar{E}_2^{FK}]$ and $\Im[\bar{E}_6^{FK}]$ are 0 by the proposed formulae and can also be considered as substantially 0 in the numerical calculations, as the calculated values were at most about $\Re[\bar{E}_2^{FK}]$ = 0.01 and $\Im[\bar{E}_6^{FK}]$ = 0.002. This means that it is appropriate to consider the center of action of Froude-Krylov force in the *y* direction is at the LCB. The proposed formulae consider the hull-form to be box-shaped with the dimensions $LC_w \times B \times dC_{vp}$, which is the same as for $\bar{E}_3^{FK}$ and $\bar{E}_5^{FK}$. Section 3.3 explained that the accuracy of the *z* direction Froude-Krylov force decreased in the short wave length region of longitudinal waves if the hull form is considered as box-shaped. On the contrary, because the force in the *y* direction in longitudinal waves is inherently 0, the formulae for $\bar{E}_2^{FK}$ and $\bar{E}_6^{FK}$ possess sufficient accuracy for practical application even without the correction like Eq. (33).

If the simplified formula for sway shown as Eq. (44) is expanded by *k*, agreement of its asymptotic value in the long wave length range with the exact value given by Eq. (14) can be confirmed. However, when the simplified formula for yaw in Eq. (45) is expanded to the second order of *k*, it is expressed as follows:

$$\bar{E}_6^{FK} \sim \bar{k}_w \bar{k}_l \frac{d}{B} \frac{C_w C_b^2}{12} \qquad \text{as} \quad k \to 0 \tag{46}$$

Comparing the right sides of the above Eq. (46) and the exact equation Eq. (15), the following correspondence can be observed:

$$\frac{1}{L^3 B d} \int_{V_H} (x^2 - y^2) \mathrm{d}V \;\leftrightarrow\; \frac{C_w C_b^2}{12} \tag{47}$$

The equivalent draft was assumed to be $d_e = dC_{vp}^2$ for $\bar{E}_6^{FK}$ as a result of considering the correspondence shown in Eq. (47). That is, the right side of Eq. (47) derived by assuming $d_e = dC_{vp}^2$ is a good approximation of the integral of the left side. If the equivalent draft d_e is assumed to be $d_e = dC_{vp}$, i.e., the same as for $\bar{E}_2^{FK}$, the right side of (47) becomes $C_w^2 C_b/12$, and its approximation accuracy will decrease. In fact, it was found that the overall estimation accuracy of $\bar{E}_6^{FK}$ when the equivalent draft was assumed to be dC_{vp}^2 was higher than when dC_{vp} was assumed.

3.5 Roll

First, the section Froude-Krylov moment around the *x*-axis (waterline height) and the Froude-Krylov moment are written as $\bar{f}_{4O}^{FK}(\bar{x})$ and $\bar{E}_{4O}^{FK}$, respectively, and from the definitional equation (5) of n_4, the relationship of the values $\bar{f}_4^{FK}(\bar{x})$ and $\bar{E}_4^{FK}$ around the center of gravity is as follows:

$$\begin{aligned} \bar{f}_4^{FK}(\bar{x}) &= \bar{f}_{4O}^{FK}(\bar{x}) + \bar{z}_G \bar{f}_2^{FK}(\bar{x}) \\ \bar{E}_4^{FK} &= \bar{E}_{4O}^{FK} + \bar{z}_G \bar{E}_2^{FK} \end{aligned} \tag{48}$$

In the following, the moments $\bar{f}_{4O}^{FK}(\bar{x})$ and $\bar{E}_{4O}^{FK}$ around the *x*-axis will be considered.

When the section shape is considered as a rectangle with breadth $B'(\bar{x})$ and depth $d'(\bar{x})$, the section Froude-Krylov moment $\bar{f}_{4O}^{FK}(\bar{x})$ is as shown by the following equation.

$$\begin{aligned} \bar{f}_{4O}^{FK}(\bar{x}) = {} & ie^{-i\bar{k}_l \bar{x}} \left\{ \frac{2}{KB} \sin \frac{\bar{k}_w \bar{B}'(\bar{x})}{2} \right\} \left[\frac{1 - \{1 + kd'(\bar{x})\} e^{-kd'(\bar{x})}}{KB} \right] \\ & - ie^{-i\bar{k}_l \bar{x} - kd'(\bar{x})} \frac{1}{\bar{k}_w} \left\{ \frac{2}{\bar{k}_w} \sin \frac{\bar{k}_w \bar{B}'(\bar{x})}{2} - \bar{B}'(\bar{x}) \cos \frac{\bar{k}_w \bar{B}'(\bar{x})}{2} \right\} \end{aligned} \tag{49}$$

The first term on the right side is the contribution from the left and right side walls, and the second term is the contribution from the bottom surface. Although Eq. (49) is the similar to the simplified estimation formula for the effective wave slope coefficient proposed by Umeda et al. [11)]. However, in the estimation method for E_4^{FK} according to Umeda et al., the information for $d'(x)$ and $B'(x)$ is given for each transverse section, and numerical integration of $f_4^{FK}(x)$ is required. Thus, while the estimation accuracy of the coefficient proposed by Umeda et al. is high, the number of parameters considered necessary is also correspondingly large.

Here, Eq. (49) is substituted into Eq. (7), the approximation shown as Eq. (24) is applied to the first term on the right side of Eq. (49) and the following approximation is applied to the second term.

$$\frac{2}{\bar{k}_w} \sin \frac{\bar{k}_w \bar{B}'}{2} - \bar{B}' \cos \frac{\bar{k}_w \bar{B}'}{2} \cong \bar{B}'^3 \left(\frac{2}{\bar{k}_w} \sin \frac{\bar{k}_w}{2} - \cos \frac{\bar{k}_w}{2} \right) \tag{50}$$

The approximation in Eq. (50) is based on the fact that the leading term when the left side is expanded by $\bar{k}_w$ is proportional to $\bar{B}'^3$. Furthermore, because the first and second terms on the right side of (49) are integrals related to n_y and n_z, respectively, different shape approximations should be performed by the two. These are distinguished by using the different equivalent drafts d_{e1} and d_{e2} and breadths $\bar{B}_1'(\bar{x})$ and $\bar{B}_2'(\bar{x})$, respectively. Based on the above, $\bar{E}_{4O}^{FK}$ is expressed as shown in Eq. (51):

$$\bar{E}_{40}^{FK} \cong i\left\{\frac{1-(1+kd_{e1})e^{-kd_{e1}}}{kB}\right\}\left(\frac{2}{kB}\sin\frac{\bar{k}_w}{2}\right)\int_{\bar{x}_A}^{\bar{x}_F}\bar{B}_1'(\bar{x})e^{-i\bar{k}_l\bar{x}}\mathrm{d}\bar{x} - ie^{-kd_{e2}}\frac{1}{\bar{k}_w}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}-\cos\frac{\bar{k}_w}{2}\right)\int_{\bar{x}_A}^{\bar{x}_F}\{\bar{B}_2'(\bar{x})\}^3e^{-i\bar{k}_l\bar{x}}\mathrm{d}\bar{x} \tag{51}$$

Continuing, let us consider the approximate value of the integrals of the right side of Eq. (51). Because the first term on the right side of Eq. (51), i.e., the term associated with the side walls, is strong influenced by the draft as the lever of the moment, let $d_{e1} = d$. Assuming that $\bar{B}_1'(\bar{x})$ is a rectangle with an area C_b centered on LCB:

$$\bar{B}_1'(\bar{x}) = \begin{cases} 1 & \text{for} \quad |\bar{x}| \le C_b/2 \\ 0 & \text{otherwise} \end{cases} \tag{52}$$

LCB was assumed as the center because it was inferred that this term is the same as $\bar{E}_2^{FK}$ and $\bar{E}_6^{FK}$, as it is an integral related to n_y, and the area was assumed to be C_b so that the integral value of $d_{e1}B_1'(x)$ is identical to the displacement volume. Under these assumptions, the first term on the right side of Eq. (51) can be expressed as follows:

$$(\text{First term}) = i\left\{\frac{1-(1+kd)e^{-kd}}{kB}\right\}\left(\frac{2}{kB}\sin\frac{\bar{k}_w}{2}\right)\left(\frac{2}{\bar{k}_l}\sin\frac{C_b\bar{k}_l}{2}\right) \tag{53}$$

Next, the second term on the right side of Eq. (51), that is, the term associated with the bottom surface, is an integral related to n_z. Therefore, as in the Froude-Krylov forces of heave and pitch, $d_{e2} = dC_{vp}$, and $\bar{B}_2'(\bar{x})$ is considered to be equivalent to the waterline breadth $\bar{B}_w'(\bar{x})$ and is considered as having a trapezoidal distribution with an area of C_w centered on LCF:

$$\bar{B}_2'(\bar{x}) = \begin{cases} 1 & \text{for} \quad |\bar{x}-\bar{x}_f| \le C_w - 0.5 \\ \dfrac{0.5-|\bar{x}|}{1-C_w} & \text{for} \quad C_w - 0.5 < |\bar{x}-\bar{x}_f| \le 0.5 \end{cases} \tag{54}$$

If the geometry of Eq. (54) is adopted, the expression of the integral value $\{\bar{B}_2'(\bar{x})\}^3e^{-i\bar{k}_l\bar{x}}$ will be complex. Therefore, simplification is performed without reducing estimation accuracy in beam sea using the fact that the ship longitudinal distribution of the incident wave front expressed by $e^{-i\bar{k}_l\bar{x}}$ is $e^{-i\bar{k}_l\bar{x}} = 1$ in a beam sea. That is, in a beam sea, the integral value of $\{\bar{B}_2'(\bar{x})\}^3e^{-i\bar{k}_l\bar{x}}$ using Eq. (54) with a trapezoidal distribution can be expressed simply, as follows:

$$\int_{\bar{x}_A}^{\bar{x}_F}\{\bar{B}_2'(\bar{x})\}^3\mathrm{d}\bar{x} = \frac{3C_w-1}{2} \tag{55}$$

Based on this fact, if the distribution of $\bar{B}_2'(\bar{x})$ can be considered as a "rectangular distribution with an area of $(3C_w - 1)/2$ centered on LCF," complexification of the integral can be avoided while maintaining accuracy in beam seas. In this case, the integral in the second term on the right side of Eq. (51) can be expressed as shown in Eq. (56).

$$\int_{\bar{x}_A}^{\bar{x}_F}\{\bar{B}_2'(\bar{x})\}^3e^{-i\bar{k}_l\bar{x}}\mathrm{d}\bar{x} = e^{-i\bar{k}_l\bar{x}_f}\frac{2}{\bar{k}_l}\sin\frac{(3C_w-1)\bar{k}_l}{4} \tag{56}$$

As a result, the second term on the right side of Eq. (51) becomes the following:

$$(\text{Second term}) = -ie^{-i\bar{k}_l\bar{x}_f - kdC_{vp}}\frac{1}{\bar{k}_w}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}-\cos\frac{\bar{k}_w}{2}\right)\left\{\frac{2}{\bar{k}_l}\sin\frac{(3C_w-1)\bar{k}_l}{4}\right\} \tag{57}$$

Finally, the following simplified formula was obtained as the Froude-Krylov moment of roll around the center of gravity:

$$\bar{E}_4^{FK} = i\left\{\frac{1-(1+kd)e^{-kd}}{kB}\right\}\left(\frac{2}{kB}\sin\frac{\bar{k}_w}{2}\right)\left(\frac{2}{\bar{k}_l}\sin\frac{C_b\bar{k}_l}{2}\right) \\ -ie^{-i\bar{k}_l\bar{x}_f-kdC_{vp}}\frac{1}{\bar{k}_w}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}-\cos\frac{\bar{k}_w}{2}\right)\left\{\frac{2}{\bar{k}_l}\sin\frac{(3C_w-1)\bar{k}_l}{4}\right\} \quad +\bar{z}_G\bar{E}_2^{FK} \tag{58}$$

Figure 8 shows the comparison with the numerical calculation values for the developed simplified formula shown in Eq. (58). Although a slight reduction in accuracy can be seen in the short wave length region, it can be understood that this formula has sufficient practical accuracy as a simplified formula.

When the terms on the right side of the proposed formula in Eq. (58) are expanded by k, the results for the respective terms asymptotically approach the following values:

$$(\text{First term}) \sim -i\bar{k}_w\frac{dC_b}{B^2}\left\{-\frac{d}{2}\right\} \qquad \text{as} \quad k\to 0 \tag{59}$$

$$(\text{Second term}) \sim -i\bar{k}_w\frac{dC_b}{B^2}\left\{\frac{B^2}{dC_b}\frac{(3C_w-1)}{24}\right\} \qquad \text{as} \quad k\to 0 \tag{60}$$

$$(\text{Third term}) \sim -i\bar{k}_w\frac{dC_b}{B^2}\{-z_G\} \qquad \text{as} \quad k\to 0 \tag{61}$$

When compared with the exact value given by Eq. (16), it can be seen that the sum of the contents enclosed in the curly brackets in Eqs. (59) to (61) is in agreement with GM, and in order from the top, these contents correspond to z_B, BM and $-z_G$ on the right side of Eq. (20). Because shape of the side walls is approximated as box-shape in the first item (i.e., Eq. (59)), $z_B = -d/2$. In the second item (Eq. (60)), from Eqs. (20) and (55), the waterline breadth $\bar{B}_w(\bar{x})$ becomes BM when approximated by a trapezoidal distribution. In formulation of the second term, if the distribution of $\bar{B}_2'(\bar{x})$ is simply approximated by a rectangle having area C_w, the result will diverge from the actual value of BM, resulting in a decrease in accuracy in the long wave length region. Accompanying this, a decrease in accuracy in the short wave length region was also confirmed. Although the right side of Eq. (55) was used in the area of the distribution of $\bar{B}_2'(\bar{x})$ to maintain accuracy in beam seas, this also leads to improved estimation accuracy under all wave conditions.

3.6 Formulae of Pitch/Roll Moment Using Longitudinal/Transverse Metacentric Height

As explained previously, Eq. (35) for the pitch moment $\bar{E}_5^{FK}$ shown in the earlier section 3.3 and Eq. (58) for the roll moment $\bar{E}_4^{FK}$ in section 3.5 asymptotically approach values approximating the restoring force coefficient, which is the exact asymptotic value in the long wave length region. In contrast, if it is acceptable to use the restoring force coefficient of a ship, that is, the longitudinal/transverse metacentric heights, in the formula, formulae for $\bar{E}_5^{FK}$ and $\bar{E}_4^{FK}$ which take the exact asymptotic values can be expressed. Therefore, this section describes the expression of $\bar{E}_5^{FK}$ and $\bar{E}_4^{FK}$ using the longitudinal and transverse metacentric heights, and compares the results with those of formulae shown in Eq. (35) and Eq. (58), which were already developed.

First, let us consider the equation for $\bar{E}_5^{FK}$. In formula in Eq. (35) for $\bar{E}_5^{FK}$, the $C_w\bar{k}_l'$ dependent functions are transformed as shown below:

$$\frac{1}{\bar{k}_l'}\left\{\frac{2}{\bar{k}_l'}\sin\frac{C_w\bar{k}_l'}{2}-C_w\cos\frac{C_w\bar{k}_l'}{2}\right\} = \bar{k}_l\underline{\frac{C_w^3C_b^{-0.15}}{12}}\left\{3\left(\frac{2}{C_w\bar{k}_l'}\right)^2\left(\frac{2}{\bar{k}_l'C_w}\sin\frac{C_w\bar{k}_l'}{2}-\cos\frac{C_w\bar{k}_l'}{2}\right)\right\} \tag{62}$$

From Eq. (39), the underlined portion on the right side is a quantity which corresponds to the nondimensional restoring force coefficient of pitch $dC_b/L^2\times\mathrm{GM_L}$. Therefore, the following expression of $\bar{E}_5^{FK}$ can be obtained by replacing this with $dC_b/L^2\times\mathrm{GM_L}$:

$$\bar{E}_5^{FK} = e^{-i\bar{k}_l\bar{x}_f - kdC_{vp}}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right)\left\{i\bar{k}_l\frac{dC_b}{L^2}\mathrm{GM_L}f\left(C_w\bar{k}_l'\right) - \frac{2\bar{x}_f}{\bar{k}_l'}\sin\frac{C_w\bar{k}_l'}{2}\right\} \tag{63}$$

Here, $f(x)$ is the following function, which asymptotically approaches 1 as $x \to 0$.

$$f(x) = \frac{12}{x^2}\left(\frac{2}{x}\sin\frac{x}{2} - \cos\frac{x}{2}\right) = 1 + O(x^2) \tag{64}$$

When the underlined portion in Eq. (62) is replaced with $dC_b/L^2 \times \mathrm{GM_L}$, Eq. (63) asymptotically approaches the exact value in Eq. (13) in the long wave length region, assuming the correct value of $\mathrm{GM_L}$ is used. Moreover, if $\bar{x}_f$ in Eq. (63) is neglected, it is possible to obtain a composition with an easily-understood physical meaning expressed by the product of the Smith correction factor, the wave length dependent function $f\left(C_w\bar{k}_l'\right)$, which approaches 1 in the long wave length region, and the correct asymptotic value $\bar{k}_l dC_b/L^2 \times \mathrm{GM_L}$. A slight improvement in accuracy was confirmed with Eq. (63) in comparison with Eq. (35), not only in the long wave length region, but also in the short wave length region. Accordingly, use of Eq. (63) is recommended in cases where the longitudinal metacentric height $\mathrm{GM_L}$ is known.

Next, let us consider the formula for $\bar{E}_4^{FK}$. In formula shown in Eq. (58) for $\bar{E}_4^{FK}$, when the formula is simplified on the precondition of $\beta = \pi/2$, that is, in beam sea, and k is taken to the second term by a Maclaurin expansion, $\bar{E}_4^{FK}$ is expressed as follows:

$$\bar{E}_4^{FK} = -\frac{ikdC_b}{B}\left\{\underline{-\frac{d}{2}}\left(1-\frac{2}{3}kd\right)\underline{-z_G}\left(1-kdC_{vp}\right) + \underline{\frac{B^2}{dC_b}\frac{3C_w-1}{24}}\left(1-kdC_{vp}\right)\right\} + O(k^3) \cong -ikBe^{-kdC_{vp}}\frac{dC_b}{B^2}\mathrm{GM} \tag{65}$$

Approximation on the extreme right side of Eq. (65) is a result which considers the correspondence of the sum of the underlined portion of Eq. (65) to GM, as explained in section 3.5, and $e^{-kdC_{vp}} \sim 1 - kdC_{vp}$. Although this equation was simplified by limiting its application to beam seas, in order to treat oblique waves, the following Eq. (66) was obtained by replacing kB in Eq. (65) with $\bar{k}_w$ based on the correspondence with Eq. (16), and then multiplying by a correction factor by the longitudinal nondimensional wave number $(2/C_w\bar{k}_l)\sin(C_w\bar{k}_l/2)$ (value when the water plane is approximated as a rectangle with dimensions of $C_wL \times B$).

$$\bar{E}_4^{FK} = -i\bar{k}_w e^{-kdC_{vp}}\left(\frac{2}{C_w\bar{k}_l}\sin\frac{C_w\bar{k}_l}{2}\right)\frac{dC_b}{B^2}\mathrm{GM} \tag{66}$$

The equation is very simple in comparison with Eq. (58), in which GM is not used, and is also an extremely clear equation in physical terms, as it is the product of the restoring force coefficient $dC_b/B^2 \times \mathrm{GM}$ and the wave slope of the sub-surface $\bar{k}_w e^{-kdC_{vp}}$. The accuracy of Eq. (66) when GM is known decreases slightly from that of Eq. (58) (Fig. 8) in the wave length range shorter than $\lambda/L = 0.7$, as shown in Fig. 9, but nevertheless is generally satisfactory. Furthermore, unlike Eq. (58), phase information cannot be obtained with Eq. (66), as its real part is 0. However, in comparison with Eq. (58), the asymptotic value of Eq. (66) in the long wave length region is exact, and Eq. (66) is also superior from the viewpoints of simplicity and a composition consisting of easy-to-understand physical quantities. Moreover, since the transverse metacentric height GM is a very basic quantity and is also known in many cases, Eq. (66) is considered to be amply practical as a simplified formula.

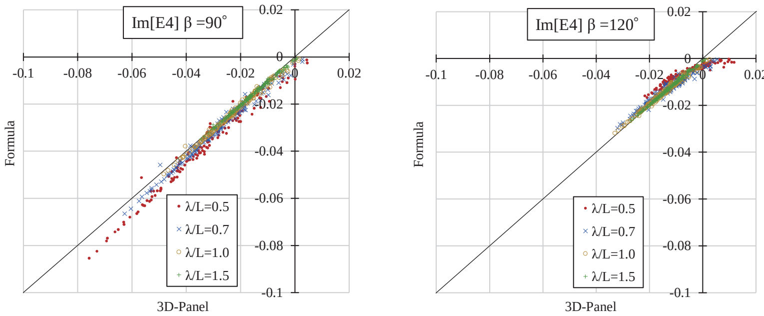


Figure 9 Comparison of $\bar{E}_4^{FK}$ between proposed Formula (66) and numerical calculation.

3.7 Points to Note in Calculations

The preceding sections have presented simplified formulae for 6 degrees of freedom. However, in calculating these simplified formulae, it is necessary to pay attention to the handling of conditions under which the denominator becomes 0. Analytically, there is no problem in taking finite limit values, but in numerical calculations, excess numerical errors or rounding errors may occur in longitudinal waves for which $\bar{k}_w$ becomes 0, and transverse waves for which $\bar{k}_l$ becomes 0, resulting in unreasonable values. In such cases, it can be avoided by the method of assigning limit values by condition branching, or normal values can be obtained more simply, by shifting the wave direction very slightly (by about 0.1°) from 0° or 90°.

Although the developed formulae are expressed by the complex amplitude, when obtaining the amplitude, it is only necessary to take the absolute values assuming $\bar{x}_f = 0$, as described in section 3.3. Where the phase is concerned, it is sufficient to calculate the argument $\arg(E_i^{FK})$ of the complex amplitude as shown in Eq. (1), but when using a solver that cannot handle complex numbers, such numbers must be divided into the real part and imaginary part. In this case, complexification of the equation can be avoided by approximation as shown in Eq. (67) and neglecting the second and higher terms of $\bar{x}_f$.

$$e^{-i\bar{k}_l\bar{x}_f} \cong 1 - i\bar{k}_l\bar{x}_f \tag{67}$$

The formula values shown in Fig. 3 to Fig. 8 were also calculated in that manner.

Care is also necessary when using the proposed formulae, the instant when the crest of a wave reaches the center of gravity position of a ship is used as a time reference. If the instant when the wave crest reaches the position $x = x_1$ is to be used as the time reference, the proposed formula E_i^{FK} should be multiplied by the phase as shown below.

$$E_i^{FK} \rightarrow e^{i\bar{k}_l\bar{x}_1}E_i^{FK} \tag{68}$$

4. CONCLUSIONS

In this paper, simplified formulae for the Froude-Krylov forces of 6 degrees of freedom (6-DOF), which are applicable without limitation of the ship type and size, were developed to enable simple estimation of ship motion in waves. The development of practical formulae of the Froude-Krylov force which can estimated only by several main dimensions of ship based on a physical discussion in this research is a new attempt without precedent in the past. The authors believe that we have succeeded in developing accurate, generally applicable formulae which are sufficient for practical application. A summary of the developed formulae and hull-form approximations is presented in Table 1.

The key points in the development of the simplified formulae are as follows.

a) In order to develop formulae that are applicable without limitation as to the ship type, an approach was adopted in which the Froude-Krylov force is expressed by an elementary function using the ship's main parameters and wave conditions as variables, by approximating the ship hull-form by functions that are uniquely determined by 8 main parameters of the ship (L, B, d, C_b, C_w, C_m, x_f (= LCF - LCG) and KG). For the pitch and roll moments, formulae supposing cases in which the longitudinal metacentric height GM_L and the transverse metacentric height GM are known were also proposed.

b) In approximation of the ship hull-form, the hull-form is approximated by an appropriate shape for each of the 6 DOFs based on geometrical considerations and the shape that results in a correct asymptotic value in the long wave length region.

It is known that the asymptotic value of the Froude-Krylov force in the long wave length region corresponds to the restoring force coefficient. The asymptotic values of the proposed formulae approach the exact values for surge, sway and heave forces, and approach the values of the restoring force coefficient which is approximated by the main parameters for the moments of roll, pitch and yaw. Furthermore, the above-mentioned formulae for the moments of pitch and roll using the longitudinal or transverse metacentric heights approach the exact values.

c) Appropriate consideration is given to the phase difference with respect to the incident wave by assuming LCB as ship center position in terms related to n_x and n_y, and assuming LCF as ship center position in terms related to n_z.

Finally, in concluding this paper, the features and evaluation of the developed simplified formulae and the results produced thereby may be summarized as follows.

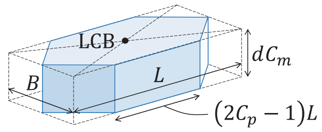
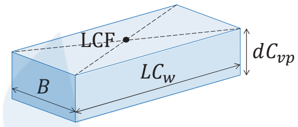
i) The proposed formulae have high estimation accuracy for 77 actual ships under two different loading conditions (full load, ballast), without limitation as to the ship type or size, under all wave direction and wave length conditions. In particular, the accuracy of the formulae increases in the longer wave length region. Because the Froude-Krylov force does not depend on the ship speed when it is based on a uniform flow approximation, these formulae can be applied to substantially all wave conditions within the range of linear theory.

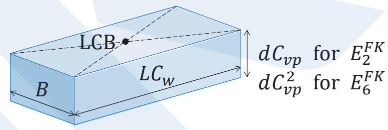
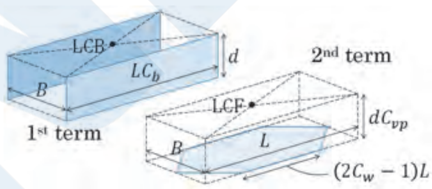
ii) Because the necessary requirements for calculations are limited to only 8 main parameters of the ship (9 in case the longitudinal/transverse metacentric heights are used), rational estimation of the Froude-Krylov force is possible even without detailed information concerning the ship's hull. This is particularly useful in evaluation of ship motility in the initial stage of design. Among the main parameters, x_f is not a general main parameter and is more difficult to obtain than the other items, but since it is a parameter that mainly influences the phase, information on x_f is not necessary when the aim is to investigate amplitude.

iii) To the best of the authors' knowledge, there are no past examples in which estimation formulae for the Froude-Krylov force expressed only by the main parameters of a ship were obtained by a theoretical approach. The research by Jensen et al. [3] for a similar purpose presented formulae for the Froude-Krylov force for a box-shaped ship, and corrected the formulae by using a fineness coefficient. In contrast, in the formulae proposed here, the complexity of the numerical expressions is essentially unchanged from those proposed by Jensen et al., but the proposed formulae are sophisticated formulae in that the influence of the ship's hull-form parameters is considered appropriately based on a geometrical consideration, and phase information can be clearly obtained. Although simplified estimation formulae which are used in stability standards exist for the Froude-Krylov moment of roll [11], information on the geometry of each transverse section of the hull is required. In contrast, reasonable estimation is possible by the proposed formulae using only the main parameters.

iv) As mentioned in the Introduction, the simplified formulae for the Froude-Krylov force have an especially high value for simplicity in estimating roll and surge. Since these are also main components among the hydrodynamic forces for other modes of motion, it is expected that the formulae developed in this research can be used effectively in simple estimations of ship motion in waves. For example, because a dominant parameter that does not exist in the motion and acceleration provisions of CSR was discovered by proposed formulae, it is expected that use of the formulae will lead to improvement of the accuracy and general applicability of the formulae.

Table 1 Summary of proposed formulae and hull-form approximations.

<table>
<tr><th>Mode</th><th>Proposed Formula</th><th>Hull-form approximation</th></tr>
<tr><td>Surge</td><td>$\bar{E}_1^{FK} = i(1-e^{-kdC_m})\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right)\left(\frac{2}{kL}\sin\frac{C_p\bar{k}_l}{2}\right)\left\{\frac{2}{(1-C_p)\bar{k}_l}\sin\frac{(1-C_p)\bar{k}_l}{2}\right\}$</td><td>
</td></tr>
<tr><td>Heave</td><td>$\bar{E}_3^{FK} = e^{-i\bar{k}_l\bar{x}_f-kdC_{vp}}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right)\left(\frac{2}{\bar{k}_l'}\sin\frac{C_w\bar{k}_l'}{2}\right)$</td><td rowspan="2">

+ Correction for $\bar{k}_l \to C_b^{-0.15}\bar{k}_l$</td></tr>
<tr><td>Pitch around COG</td><td>$\bar{E}_5^{FK} = ie^{-i\bar{k}_l\bar{x}_f-kdC_{vp}}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right)\frac{1}{\bar{k}_l'}\left\{\left(\frac{2}{\bar{k}_l'}+2i\bar{x}_f\right)\sin\frac{C_w\bar{k}_l'}{2}-C_w\cos\frac{C_w\bar{k}_l'}{2}\right\}$
$\bar{E}_5^{FK} = ie^{-i\bar{k}_l\bar{x}_f-kdC_{vp}}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}\right)\left\{\bar{k}_l\frac{dC_b}{L^2}\mathrm{GM_L}f(C_w\bar{k}_l')+\frac{2i\bar{x}_f}{\bar{k}_l'}\sin\frac{C_w\bar{k}_l'}{2}\right\}$
where, $f(x)=\frac{12}{x^2}\left(\frac{2}{x}\sin\frac{x}{2}-\cos\frac{x}{2}\right)$</td></tr>
<tr><td>Sway</td><td>$\bar{E}_2^{FK} = i(1-e^{-kdC_{vp}})\left(\frac{2}{kB}\sin\frac{\bar{k}_w}{2}\right)\left(\frac{2}{\bar{k}_l}\sin\frac{C_w\bar{k}_l}{2}\right)$</td><td rowspan="2">
</td></tr>
<tr><td>Yaw around COG</td><td>$\bar{E}_6^{FK} = (1-e^{-kdC_{vp}^2})\left(\frac{2}{kB}\sin\frac{\bar{k}_w}{2}\right)\frac{1}{\bar{k}_l}\left(\frac{2}{\bar{k}_l}\sin\frac{C_w\bar{k}_l}{2}-C_w\cos\frac{C_w\bar{k}_l}{2}\right)$</td></tr>
<tr><td>Roll around COG</td><td>$\bar{E}_4^{FK} = i\left\{\frac{1-(1+kd)e^{-kd}}{kB}\right\}\left(\frac{2}{kB}\sin\frac{\bar{k}_w}{2}\right)\left(\frac{2}{\bar{k}_l}\sin\frac{C_b\bar{k}_l}{2}\right)$
$-ie^{-i\bar{k}_l\bar{x}_f-kdC_{vp}}\frac{1}{\bar{k}_w}\left(\frac{2}{\bar{k}_w}\sin\frac{\bar{k}_w}{2}-\cos\frac{\bar{k}_w}{2}\right)\left\{\frac{2}{\bar{k}_l}\sin\frac{(3C_w-1)\bar{k}_l}{4}\right\}$
$+\bar{z}_G\bar{E}_2^{FK}$
$\bar{E}_4^{FK} = -i\bar{k}_w e^{-kdC_{vp}}\left(\frac{2}{C_w\bar{k}_l}\sin\frac{C_w\bar{k}_l}{2}\right)\frac{dC_b}{B^2}\mathrm{GM}$</td><td>
</td></tr>
<tr><td colspan="3">Where: $C_p=\frac{C_b}{C_m}$, $C_{vp}=\frac{C_b}{C_w}$, $\bar{k}_l = kL\cos\beta$, $\bar{k}_w = kB\sin\beta$, $\bar{k}_l' = C_b^{-0.15}\bar{k}_l$, $\bar{x}_f=\frac{\mathrm{LCF}-\mathrm{LCG}}{L}$, $\bar{z}_G=\frac{\mathrm{KG}-d}{B}$</td></tr>
</table>

ACKNOWLEDGMENT

The authors wish to express their profound gratitude to Dr. Toichi Fukasawa and Dr. Takako Kuroda of the National Maritime Research Institute (NMRI) for their appropriate advice in conducting this research and preparing the paper, and to Dr. Hiroshi Kawabe and Mr. Yusuke Fukumoto of Nippon Kaiji Kyokai (ClassNK), Mr. Tatsuya Akamatsu of Nippon Yusen Kaisha (NYK Line), Mr. Tomoki Omiya, Mr. Kumpei Wakida and Mr. Kazushi Kuzuya of Mitsui O.S.K. Lines, Ltd. and Mr. Junya Matsuwaki of Imabari Shipbuilding Co., LTD. for their cooperation in the data analysis in this research.

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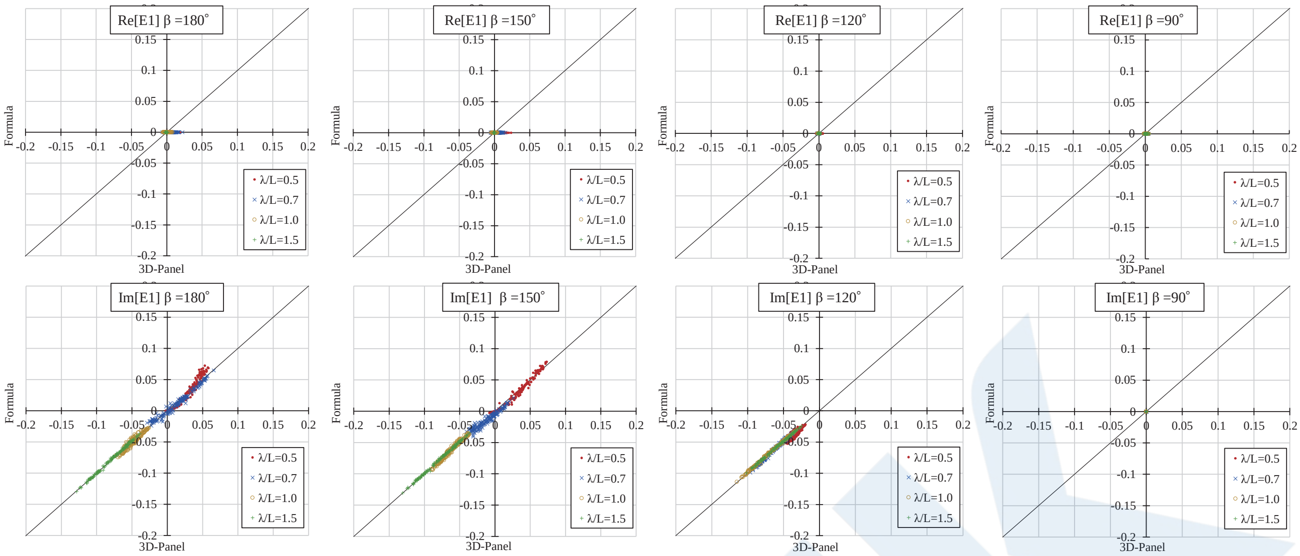

Figure 3　Comparison of $\bar{E}_1^{FK}$ between proposed formula and numerical calculation for target ships.

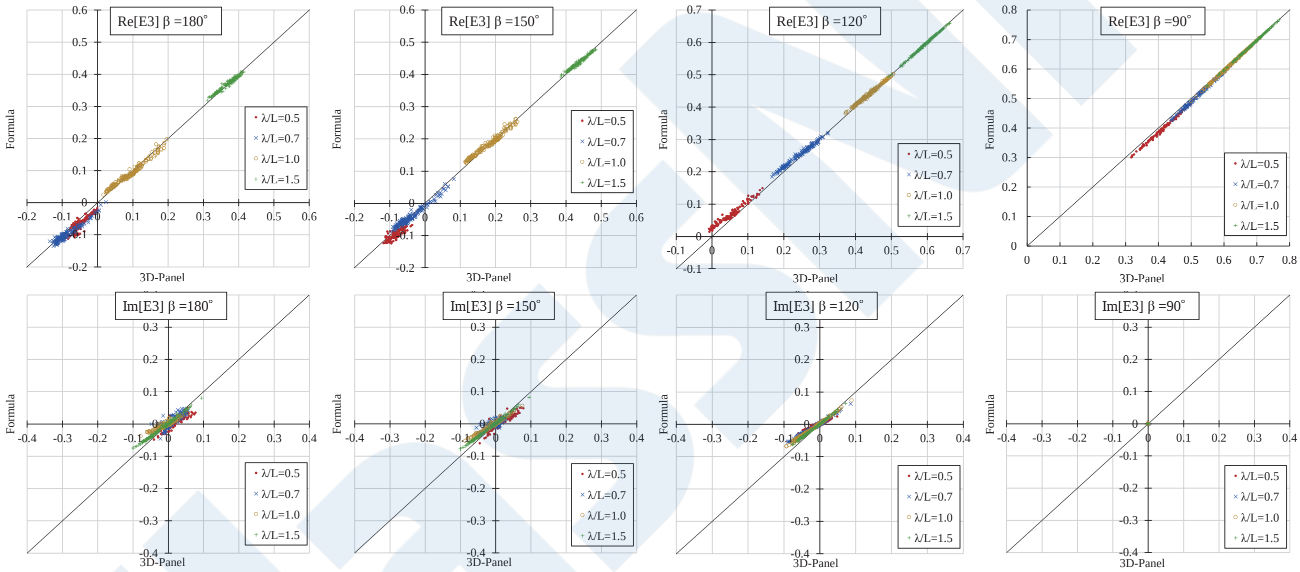

Figure 4　Comparison of $\bar{E}_3^{FK}$ between proposed formula and numerical calculation for target ships.

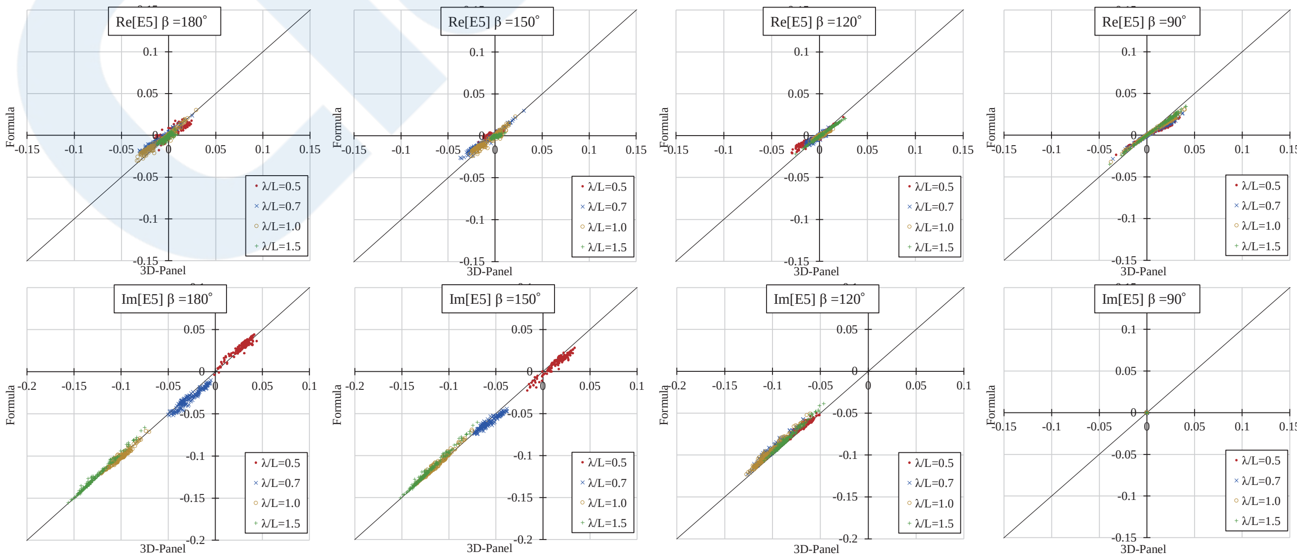

Figure 5　Comparison of $\bar{E}_5^{FK}$ between proposed formula and numerical calculation for target ships.

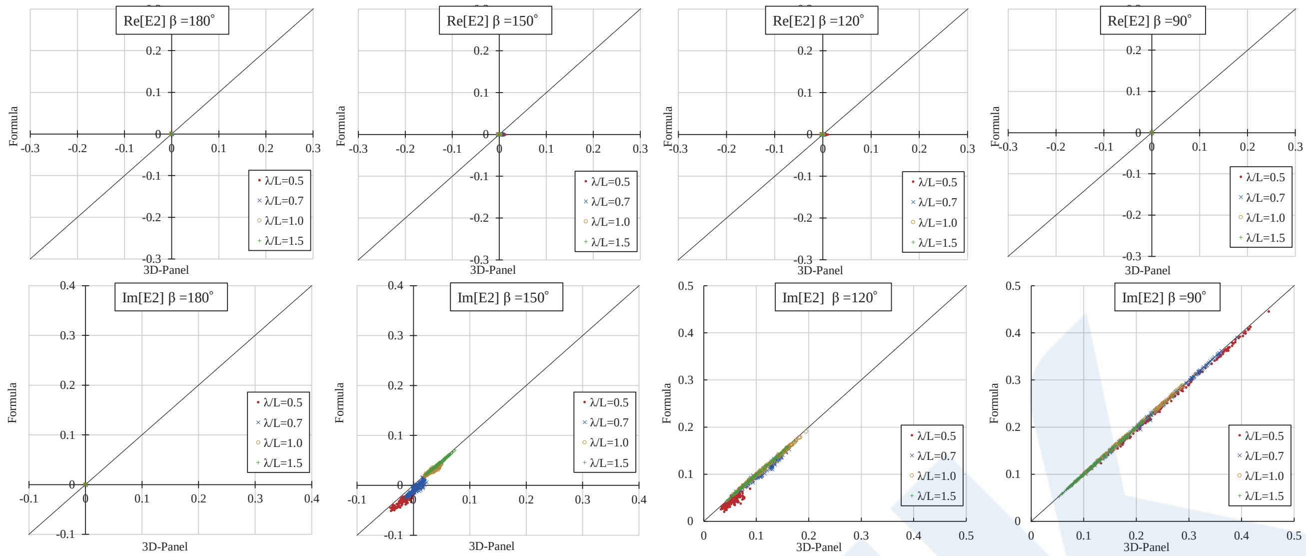

Figure 6　Comparison of $\bar{E}_2^{FK}$ between proposed formula and numerical calculation for target ships.

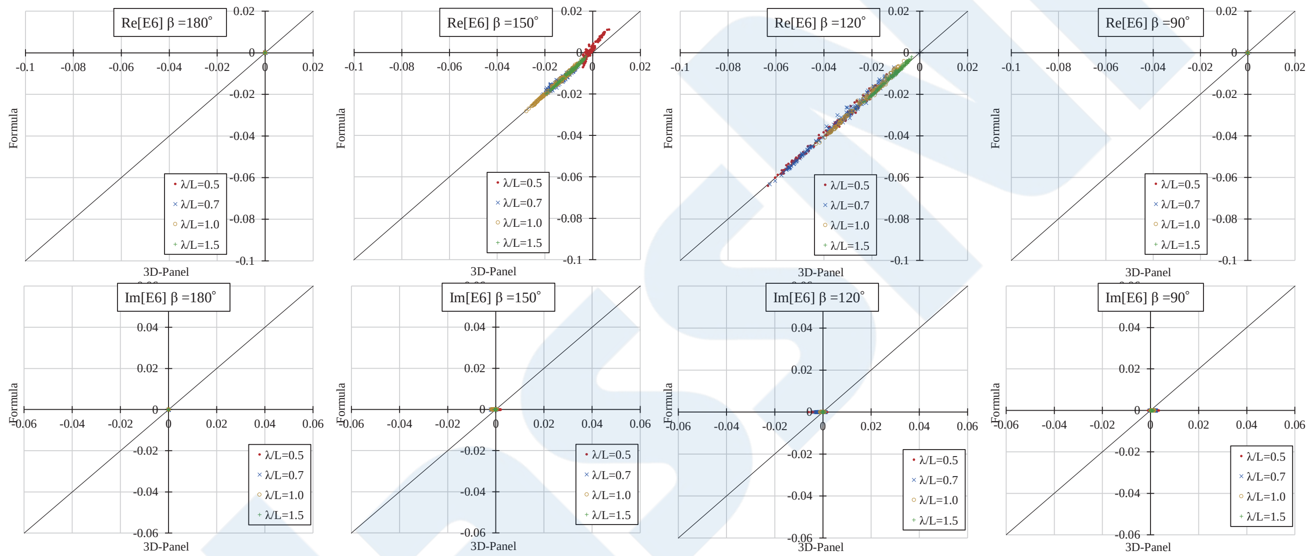

Figure 7　Comparison of $\bar{E}_6^{FK}$ between proposed formula and numerical calculation for target ships.

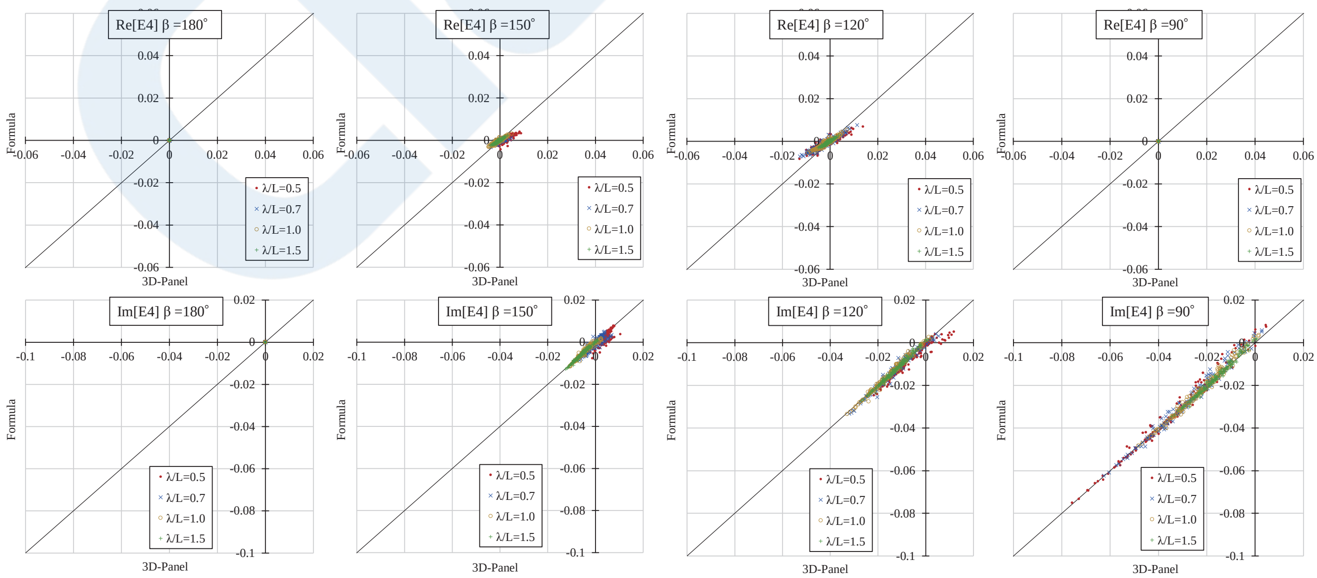

Figure 8　Comparison of $\bar{E}_4^{FK}$ between proposed formula and numerical calculation for target ships.

Development of Closed Formula of Wave Load Based Upon Long-Term Prediction[*1]

— Heave Acceleration and Pitch Angle —

Kyohei SHINOMOTO[*], Sadaoki MATSUI[**], Kei SUGIMOTO[*], Shinsaku ASHIDA[***]

1. INTRODUCTION

Ship designers need to be able to reasonably estimate hull motion in waves from various aspects such as passenger safety, ride comfort and wave loads for ship designs. Nowadays, hull motion in waves is accurately estimated by seakeeping analysis tools such as the 3-D panel method and the estimation is practically used for all hull design and standard development [1]. At the same time, however, there also is high demand for methods which allow for more simple estimations of hull motion to be made that do not rely on numerical analysis. For example, in wave load estimations for structural strength evaluations, it can be quite difficult to perform a wave load analysis for each ship due to the amount of time it would add to the hull structure design process. For this reason, a simple estimation method based upon a simple wave load formula using main ship parameters is typically adopted for classification society rules [2] [3].

Many prior studies of this matter have estimated the maximum loads of ships through statistical prediction of hull response in irregular waves using the energy spectrum method that applies the theory of linear superposition [4] [5]. The linear term of the maximum load specified in some classification society rules [2] [3] is also specified to be equivalent to the long-term predicted value of exceedance probability of 10^{-8}. Based upon this, it can be said that long-term prediction is an established method for estimating the linear term of the maximum load.

Aim of our larger study the development of a general-purpose and high precision closed formula for maximum loads with an exceedance probability of 10^{-8} by formulating the long-term prediction for ships of any size or type. A past study by Kawabe et al. [6] had a similar purpose but proposed a method for predicting maximum loads based upon structural analysis using calculation results obtained through a strip method and the long-term prediction of stress. Moreover, since the Kawabe et al. and Shigemi et al. [7] study made no attempt to formulate the standard deviation of the hull response in irregular waves. In addition, the study only focused on bulk carriers and oil tankers, it is difficult to use its results to guarantee the accuracy for other types and sizes of ships. This study, on the other hand, takes into account the standard deviation of the hull response in irregular waves and the directional distribution of irregular waves. Main ship parameters such as ship length L, breadth B, draft d, block coefficient C_b,, and water line area coefficient C_w were used for formulating the long-term prediction. Dominant factors and their trends were examined step by step and the formula that does not limit target types and sizes of ships was developed. The accuracy of this formula was then confirmed through numerical calculations using a model to represent any type and size of ship. We believe that in this manner we were able to develop a general-purpose and high precision closed formula for practical use.

This paper focused on heave acceleration and pitch angle. Since internal loads, etc. in the structural rules require an inclined component due to rotational motion, an angle was focused on for pitch motion.

Response amplitude operator (hereinafter, referred to as “RAO”) obtained from a numerical calculation were used for RAO contained in the closed formula. The closed formula of RAO proposed by Jensen et al. [8] and Matsui et al. [9] can be used as RAO contained in the closed formula.

A flow diagram for obtaining a long-term predicted value with an exceedance probability of 10^{-8} is shown in Fig. 1. The long-term prediction can be divided into components, and these components are expressed as formulae explained in Sec. 4 onwards. The long-term prediction was formulated by developing these components using theoretical approaches as much as possible. Although we found it difficult to mathematically formulate some components, we were able to formulate them by

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taking advantage of the diversity and total number of vessels used for the numerical calculations.

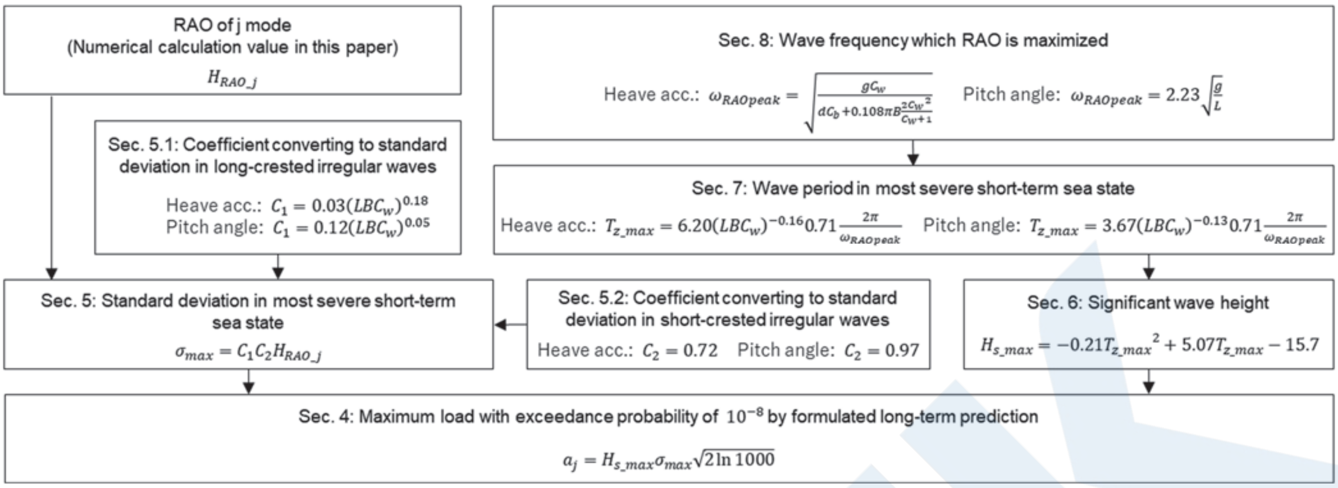
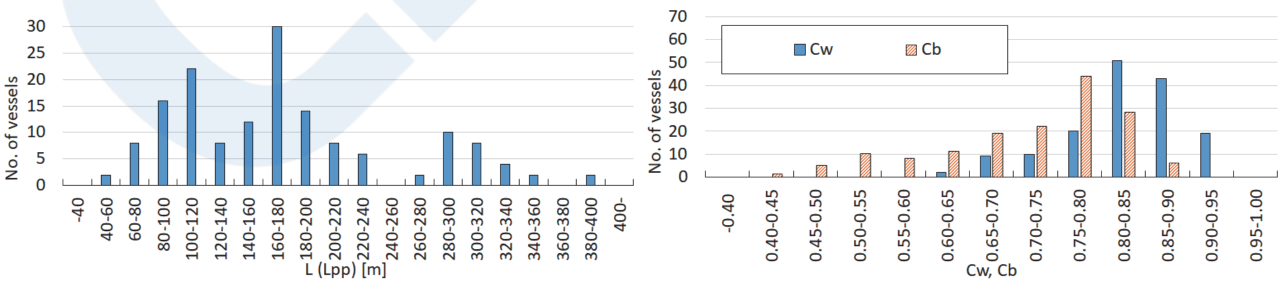


Figure 1 Flow diagram for formulated long-term prediction

2. NUMERICAL CALCULATIONS OF LINEAR ANALYSIS

In order to confirm the accuracy of our proposed closed formula, a numerical calculation with linear seakeeping analysis code developed by ClassNK was performed. The linear code is a 3-dimensional code based upon the Green function method which takes the forward speed effect approximation method proposed by Papanikolau et al. into account [10) 11)]. Sugimoto et al. validated the accuracy of this code by towing tank tests [1)]. The responses, i.e. motions and hull girder bending moment, calculated by this code and the values measured under the low-wave-height condition were in good agreement. However, it should be understood that there are some limitations to this code, and that these limitations may cause a slight discrepancy between the experimental and calculated values. One such example is the error between the experimental and calculated values that is expected to result from the fact that the panel size of the calculation model is relatively rough with respect to wavelength.

One hundred fifty-four models (77 existing ships × 2 loading conditions per ship) were used for the numerical calculation. Since the formula is intended to be applied to only general merchant ships, the target ships were limited to monohulls that had symmetrical shapes below their waterlines. As shown in Fig. 2, various types of vessels (such as bulk carriers, container carriers, wood chip carriers, general cargo carriers, liquefied gas carriers (LNG, LPG), ore carriers, oil tankers, vehicle carriers, and refrigerated carriers) were used so as to cover a wide range of values for L, C_b and C_w. In addition, forward speed was set at five knots in consideration of the decrease in ship speed with respect to high wave height, in reference to the Common Structural Rules for Bulk Carriers and Oil Tankers of the International Association of Classification Societies (hereinafter referred to as "IACS") [12)].



(A) No. of Vessels by Length (B) No. of Vessels by C_w and C_b

Figure 2 Histogram of vessels used for confirmation

3. SEA STATE CONDITIONS

As shown in Fig. 3, the scatter diagram in IACS Recommendation No. 34 [13)] was used for sea state conditions.

Hs/Tz	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	SUM
0.5	0	0	1.3	133.7	865.6	1186	634.2	186.3	36.9	5.6	0.7	0.1	0	0	0	0	0	0	3050.4
1.5	0	0	0	29.3	986	4976	7738	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	0.1	0	0	0	22575.4
2.5	0	0	0	2.2	197.5	2158.8	6230	7449.5	4860.4	2066	644.5	160.2	33.7	6.3	1.1	0.2	0	0	23810.4
3.5	0	0	0	0.2	34.9	695.5	3226.5	5675	5099.1	2838	1114.1	337.7	84.3	18.2	3.5	0.6	0.1	0	19127.7
4.5	0	0	0	0	6	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	455.1	130.9	31.9	6.9	1.3	0.2	0	13289.4
5.5	0	0	0	0	1	51	498.4	1602.9	2372.7	2008.3	1126	463.6	150.9	41	9.7	2.1	0.4	0.1	8328.1
6.5	0	0	0	0	0.2	12.6	167	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4806.3
7.5	0	0	0	0	0	3	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2586.2
8.5	0	0	0	0	0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1308.5
9.5	0	0	0	0	0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1	626.2
10.5	0	0	0	0	0	0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4	1.2	0.3	0.1	284.8
11.5	0	0	0	0	0	0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	123.6
12.5	0	0	0	0	0	0	0.1	1	4.4	9.9	12.8	11	6.8	3.3	1.3	0.4	0.1	0	51.1
13.5	0	0	0	0	0	0	0	0.3	1.4	3.5	5	4.6	3.1	1.6	0.7	0.2	0.1	0	20.5
14.5	0	0	0	0	0	0	0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0	0	7.7
15.5	0	0	0	0	0	0	0	0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0	0	2.8
16.5	0	0	0	0	0	0	0	0	0	0.1	0.2	0.2	0.2	0.1	0.1	0	0	0	0.9
SUM:	0	0	1.3	165.4	2091.2	9279.9	19921.8	24878.8	20869.9	12898.4	6244.6	2479	836.7	247.3	65.8	15.8	3.4	0.7	100000

Figure 3　IACS Rec. 34 scatter diagram [13)]

4.　CLOSED FORMULA OF LONG-TERM PREDICTION

By approximating probability distribution of responses in short-term irregular sea state in which extreme value a exceed threshold a_j by the Rayleigh distribution, multiplying it with the occurrence probability of the short-term irregular sea state and integrating it numerically, the probability $Q[a > a_j]$ of exceeding the a_j can be expressed as equation (1). This method was proposed in the mid-1960s and have been widely used as a standard method for long-term prediction in our country [14)].

$$Q[a > a_j] = \frac{1}{2\pi}\int_0^{2\pi} \langle \iint_0^{\infty} \exp\left\{-\frac{{a_j}^2}{2[H_s\sigma(T_z,\chi)]^2}\right\} p(H_s,T_z)dH_s dT_z \rangle \, d\chi \tag{1}$$

where

a	: Extreme value
a_j	: Threshold of j mode (independent variable)
H_s	: Significant wave height
$\sigma(T_z,\chi)$	: Standard deviation per unit significant wave height in short-term irregular sea state
$p(H_s,T_z)$	: Occurrence probability density of short-term irregular sea state
T_z	: Zero-up cross mean wave period in short-term irregular sea state
χ	: Mean wave direction in short-term irregular sea state

In equation (1), the angle of encounter between the waves and the ship is assumed to be uniformly distributed because a ship sailing for long periods of time is likely to encounter waves in all directions. Assuming that the mean wave period of a short-term irregular sea state is 10 seconds, the number of waves that a ship encounters throughout its lifetime is approximately 10^8. For this reason, an exceedance probability of 10^{-8} is assumed when making long-term predictions.

In this study, the most severe short-term sea state theory proposed by Kawabe et al. [6) 14) 15)] was applied: the maximum value around the exceedance probability of 10^{-8} is dominated by the hull response in the most severe short-term sea state where the short-term parameter (standard deviation of hull response $H_s\sigma(T_z,\chi)$) of the hull response is maximized in the short-term irregular sea state constituting the long-term distribution. The maximum value of the response in the short-term irregular sea state (exactly the maximum value in the zero-up-cross mean wave period) can be approximated by the Rayleigh distribution because the spectrum of the response is a narrow band. In addition, the most severe short-term sea state that causes a long-term maximum load with an exceedance probability of 10^{-8} is defined as the short-term irregular sea state with the largest short-term parameter. Therefore, the expression in 〈　〉 of equation (1) is approximated as equation (2).

$$\begin{aligned}\iint_0^{\infty} \exp\left\{-\frac{{a_j}^2}{2[H_s\sigma(T_z,\chi)]^2}\right\} p(H_s,T_z)dH_s dT_z &= \sum \exp\left[-\frac{{a_j}^2}{2\left(H_{s\_i}\sigma_i\right)^2}\right] \; p\left(H_{s\_i},T_{z\_i}\right)\Delta H_s \Delta T_z \\ &\approx \exp\left[-\frac{{a_j}^2}{2\left(H_{s\_max}\sigma_{max}\right)^2}\right] \; p\left(H_{s\_max},T_{z\_max}\right)\Delta H_s \Delta T_z\end{aligned} \tag{2}$$

where

H_{s_max} : Significant wave height in most severe short-term sea state

T_{z_max} : Zero-up cross mean wave period in most severe short-term sea state

σ_{max} : Standard deviation per unit significant wave height in most severe short-term sea state

This allows the threshold of which probability of exceedance correspond to 10^{-8} to be approximated as equation (3).

$$a_j|_{Q=10^{-8}} \approx \frac{1}{2\pi}\int_0^{2\pi} \exp\left[-\frac{{a_j}^2}{2\left(H_{s\_max}\sigma_{max}\right)^2}\right] \times p\left(H_{s\_max}, T_{z\_max}\right)\Delta H_s \Delta T_z \ d\chi \tag{3}$$

Assuming that the duration of the short-term irregular sea state is two hours, the number of times the ship encounters the short-term irregular sea state throughout its lifetime is approximately 10^5. From this, the occurrence probability of the maximum hull response in the most severe short-term sea state is approximately taken to be 10^{-3} $(= 10^{-8}/10^{-5})$ when the occurrence probability of the maximum hull response is assumed to be 10^{-8}. By calculating the maximum expected value for 1000 waves in the short-term irregular sea state, a load equivalent to the maximum load with an exceedance probability of 10^{-8} can therefore be obtained. The maximum load with an exceedance probability of 10^{-3} can be expressed as equation (4).

$$a_j = H_{s\_max}\sigma_{max}\sqrt{2\ln 1000} \tag{4}$$

In this paper, Equation (4) is used as the base of the closed formula with an exceedance probability of 10^{-8}.

The mean wave direction in the most severe short-term sea state of heave acceleration and pitch angle were able to be obtained through the long-term prediction result of the numerical calculation and were as shown in Fig. 4. From this result, the mean wave directions in the most severe short-term sea state were set to 90 degrees and 180 degrees (heading wave) respectively.

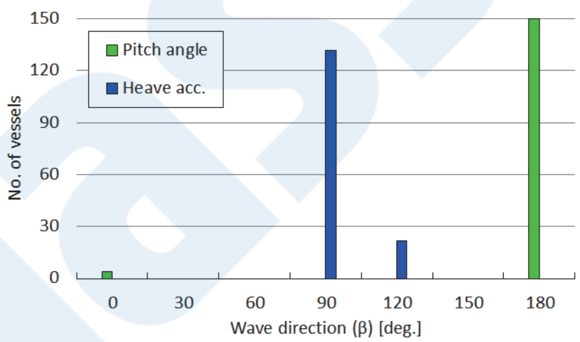


Figure 4　Mean wave direction in most severe short-term sea state

5.　STANDARD DEVIATION IN THE MOST SEVERE SHORT-TERM SEA STATE

The standard deviation σ_{max} per unit significant wave height in the most severe short-term sea state is expressed as equation (5) approximately.

$$\sigma_{max} = C_1 C_2 H_{RAO\_j} \tag{5}$$

where

C_1 : Conversion coefficient for converting RAO to standard deviation per unit significant wave height

C_2 : Conversion coefficient for converting long-crested irregular wave to short-crested irregular wave

H_{RAO_j} : Maximum value of RAO of j mode

5.1 Converting to Standard Deviation per Unit Significant Wave Height

A RAO is converted to σ in order to obtain the standard deviation per unit significant wave height. Since the energy spectrum method applying the theory of linear superposition is generally used when performing short-term prediction, σ is expressed as equation (6).

$$\sigma = \sqrt{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_0^{\infty} H_{RAO\_j}(\omega, \chi - \beta)^2 S(\omega, T_z) D(\chi - \beta)\, d\omega\, d\beta} \tag{6}$$

where

$H_{RAO\_j}(\omega,\beta)$	: RAO of j mode
$S(\omega,T_z)$	: Pierson-Moskowitz type wave spectrum per unit significant wave height
$D(\beta)$	: Directional distribution function
ω	: Wave frequency
β	: Direction of wave component

The term excluding the directional distribution function in equation (6) was conveniently divided by the maximum value of RAO, and equation (7) is given for the conversion coefficient C_1. Note that the sea state at this time is the most severe short-term sea state.

$$C_1 = \frac{\sqrt{\int_0^{\infty} H_{RAO\_j}(\omega, \chi_{max})^2 S\left(\omega, T_{z\_max}\right) d\omega}}{H_{RAO\_j}\left(\omega_{RAOpeak}, \chi_{max}\right)} \tag{7}$$

where

$\omega_{RAOpeak}$	: Wave frequency when RAO is maximized
χ_{max}	: Mean wave direction in most severe short-term sea state

C_1 is, simply put, a coefficient for converting the RAO for a regular wave into standard deviation value in consideration of the wave spectrum shape of irregular wave. Since C_1 will differ in size depending upon hull response, it must be determined for each hull response.

Froude-krylov force is the main component of the hydrodynamic force acting on the hull required to determine the hull motion. The hydrodynamic forces affecting vertical motion, such as heave and pitch, are values integrated with respect to n_z, and thus greatly contribute to the hull shape in the z-direction projection plane area, that is, the water plane area. From this, it was considered that the C_1 values for heave acceleration and pitch angle can be expressed by the equation of the water plane area LBC_w, and determined as in equation (8).

Heave acceleration	$C_1 = 0.03(LBC_w)^{0.18}$	(8)
Pitch angle	$C_1 = 0.12(LBC_w)^{0.05}$	

Figure 5 shows a comparison of C_1 values obtained from equation (8) and numerical calculation results. Both C_1 are mostly as expected, indicating that they were able to set relatively high-precision formulae.

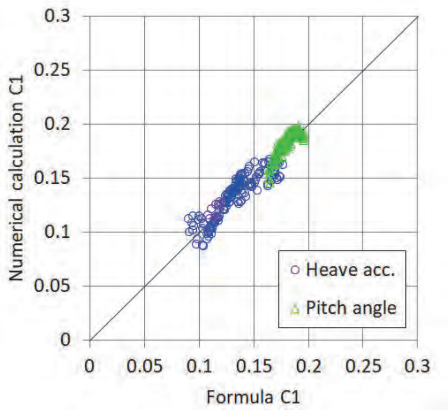


Figure 5 Comparison of equation (8) and numerical calculation C_1 values

The wave spectrum of the irregular wave used in the calculation of C_1 is the Pierson-Moskowitz type recommended by IACS Rec. 34 [13] as shown in equation (9). This wave spectrum is determined by the significant wave height and the zero-up cross mean wave period of the North Atlantic. Note that this Pierson-Moskowitz type wave spectrum equation is conveniently divided by $H_s{}^2$.

$$S(\omega, T_z) = \frac{1}{4\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-5} \exp\left[-\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-4}\right] \tag{9}$$

5.2 Converting to Standard Deviation per Unit Significant Wave Height

Although the variance σ^2 is obtained from the integral of the hull response spectrum, this value is that of a long-crested irregular wave. The wave fields encountered under actual sea conditions are rarely long-crested irregular waves but rather short-crested irregular waves in which irregular waves arriving from various directions overlap. For a more accurate statistical prediction, the σ^2 needs to be converted to value for short-created irregular waves. That is to say, a short-crested irregular wave having a set of wave components of different frequencies and a planar spread is approximately represented by using a directional distribution function $D(\beta)$ as shown in equation (10) [16].

$$D(\beta) = \frac{(2n)!}{\pi(2n-1)!}[\cos(\chi - \beta)]^{2n} \qquad \left(-\frac{\pi}{2} \le \beta \le \frac{\pi}{2}\right) \tag{10}$$

In the short-term prediction of a hull response of the Fukuda method [17], equation (11) where n=1 is often used.

$$D(\beta) = \frac{2}{\pi}[\cos(\chi - \beta)]^2 \qquad \left(-\frac{\pi}{2} \le \beta \le \frac{\pi}{2}\right) \tag{11}$$

Assuming that the standard deviation of the short-crested irregular wave is σ_{short} and the standard deviation of the long-crested irregular wave is σ_{long}, σ_{short} can be expressed as equation (12).

$$\sigma_{short} = \sqrt{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \sigma_{long}{}^2 D(\chi - \beta)\, d\beta} \tag{12}$$

where

σ_{short} Standard deviation in short-crested irregular waves

σ_{long} Standard deviation in long-crested irregular waves

The coefficient C_2 that converts long-crested irregular wave to short-crested irregular wave in most severe short-term sea state was defined by equation (13).

$$C_2 = \frac{\sigma_{short}(T_{z\_max}, \chi_{max})}{\sigma_{long}(T_{z\_max}, \chi_{max})} \tag{13}$$

Since the ratio of hull response for each wave direction is basically the same regardless of the size of the ship when considering a hull motion, it can be inferred that C_2 is almost constant. From numerical calculation results, it can also be confirmed that C_2 is plotted as shown in Fig. 6, and its tendency is almost as estimated.

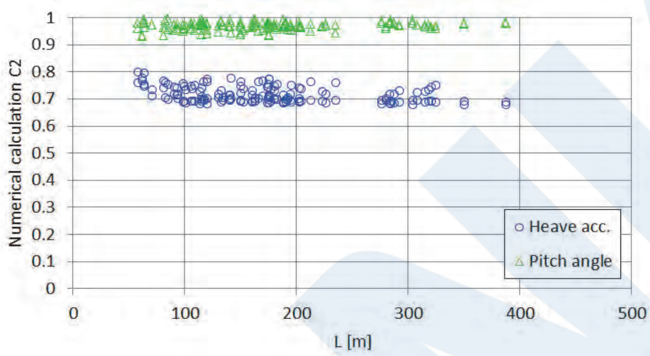


Figure 6 Numerical calculation C_2 values

From Fig. 6, the C_2 was expressed as shown in equation (14).

$$\begin{aligned} &\text{Heave acceleration} \qquad && C_2 = 0.72 \\ &\text{Pitch angle} && C_2 = 0.97 \end{aligned} \tag{14}$$

6. SIGNIFICANT WAVE HEIGHT IN THE MOST SEVERE SHORT-TERM SEA STATE

The probability model [18] used in this study is a joint probability distribution of the conditional probability distribution of the wave period with respect to the significant wave height (log normal distribution) and the marginal probability distribution of the significant wave height (Weibull distribution) as shown in equation (15).

$$p(T_z|H_s)p(H_s) = \frac{1}{T_z\sqrt{2\pi\sigma_T(H_s)}} \exp\left\{-\frac{[ln\, T_z - m_T(H_s)]^2}{2\sigma_T{}^2(H_s)}\right\} \times \frac{\beta(H_s-\gamma)^{\beta-1}}{\alpha^\beta} \exp\left[-\left(\frac{H_s-\gamma}{\alpha}\right)^\beta\right] \tag{15}$$

where

α : Scale parameter

β : Shape parameter

γ : Threshold

with $m_T(H_s)$ and $\sigma_T{}^2(H_s)$ obtained as shown in equation (16).

$$\begin{aligned} m_T(H_s) &= E(\ln T_z(H_s)) \\ \sigma_T{}^2(H_s) &= Var(\ln T_z(H_s)) \end{aligned} \tag{16}$$

The scatter diagram given in IACS Rec. 34 [13] shown in Fig. 3 was used and the occurrence probability of the short-term irregular sea state of equation (15) was 10^{-5}, the significant wave height at that probability can be determined by polynomial approximation as shown in equation (17).

$$H_{s\_max} = -0.21{T_{z\_max}}^2 + 5.07T_{z\_max} - 15.7 \tag{17}$$

Equation (17) is plotted as Fig. 7. From Fig. 7, it can be seen that equation (17) represents the significant wave height of a sea state with an extremely low frequency of occurrence. Incidentally, the short-term irregular sea state in which the joint probability in the scatter diagram is 10^{-5} is generally circular distribution (there is a case where two short-term irregular sea states occur in a zero-up cross mean wave period). However, since the higher significant wave height of the wave heights is generally used in ship design, the approximate expression of the significant wave height is made to be a second order polynomial. The range of monotonically increasing and monotonically decreasing the significant wave height is limited, because the short-term irregular sea state in which the joint probability is 10^{-5} becomes the circular distribution. Therefore, we consider about 17.0 s to be an appropriate upper limit for the zero-up cross average wave period which is a variable of equation (17).

Hs/Tz	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	SUM
0.5	0.0	0.0	1.3	133.7	865.6	1186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	3050
1.5	0.0	0.0	0.0	29.3	986.0	4976.0	7738.0	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	0.1	0.0	0.0	0.0	22575
2.5	0.0	0.0	0.0	2.2	197.5	2158.8	6230.0	7449.5	4860.4	2066.0	644.5	160.2	33.7	6.3	1.1	0.2	0.0	0.0	23810
3.5	0.0	0.0	0.0	0.2	34.9	695.5	3226.5	5675.0	5099.1	2838.0	1114.1	337.7	84.3	18.2	3.5	0.6	0.1	0.0	19128
4.5	0.0	0.0	0.0	0.0	6.0	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	455.1	130.9	31.9	6.9	1.3	0.2	0.0	13289
5.5	0.0	0.0	0.0	0.0	1.0	51.0	498.4	1602.9	2372.7	2008.3	1126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1	8328
6.5	0.0	0.0	0.0	0.0	0.2	12.6	167.0	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4806
7.5	0.0	0.0	0.0	0.0	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2586
8.5	0.0	0.0	0.0	0.0	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1309
9.5	0.0	0.0	0.0	0.0	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1	626
10.5	0.0	0.0	0.0	0.0	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1	285
11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	124
12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0.0	51
13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0.0	21
14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0.0	0.0	8
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0.0	0.0	3
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	1
SUM:	0	0	1	165	2091	9280	19922	24879	20870	12898	6245	2479	837	247	66	16	3	1	100000

Figure 7　Plotted equation (17) on IACS Rec. 34 scatter diagram [13]

7. WAVE PERIOD IN THE MOST SEVERE SHORT-TERM SEA STATE

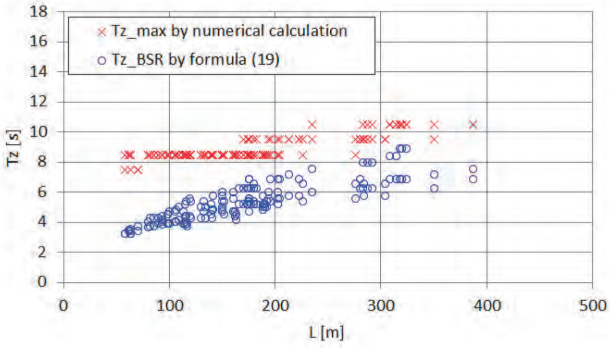
In general, wave period of the regular wave at which RAO is maximized can be expressed as in equation (18) by using wave frequency $\omega_{RAOpeak}$ at which RAO is maximized.

$$T_{RAOpeak} = \frac{2\pi}{\omega_{RAOpeak}} \tag{18}$$

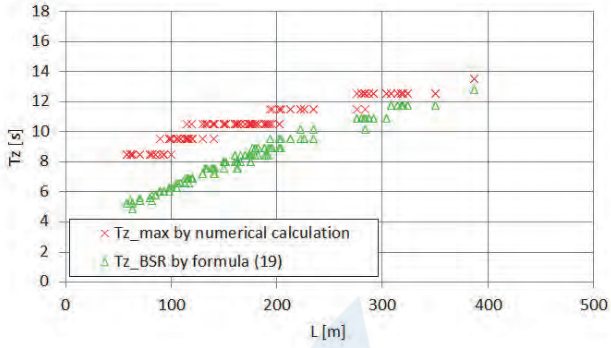
Assuming a response spectrum has narrow-band characteristics, the standard deviation value in the short-term irregular sea state is maximized when the peaks of both the wave spectrum with a mean wave period and the RAO are superimposed at the same wave frequency. This is called “broad sense of resonance” [14) 15)]. According to the assumption, the zero-up cross mean wave period of broad sense of resonance [14) 15)] T_{z_BSR} can be expressed as following equation.

$$T_{z\_BSR} = 0.71T_{RAOpeak} \tag{19}$$

The coefficient 0.71 of equation (19) means the converting factor from the peak period of wave spectrum to zero-up cross mean wave period of Pierson-Moskowitz type wave spectrum. Figure 8 shows a comparison between the zero-up cross mean wave period of broad sense of resonance T_{z_BSR} by equation (19) and the zero-up cross mean wave period for the most severe short-term sea state T_{z_max} obtained by the numerical calculation.



(A) Heave Acceleration



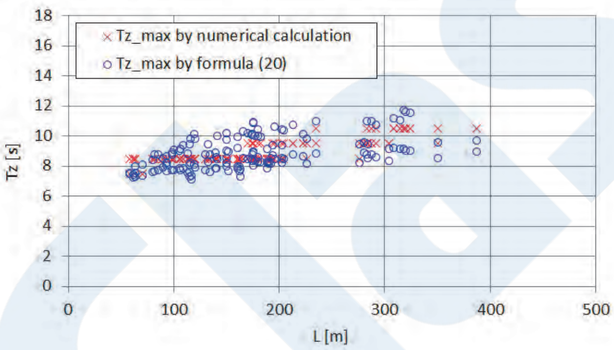
(B) Pitch Angle

Figure 8 Wave period (equation (19) and numerical calculation results)

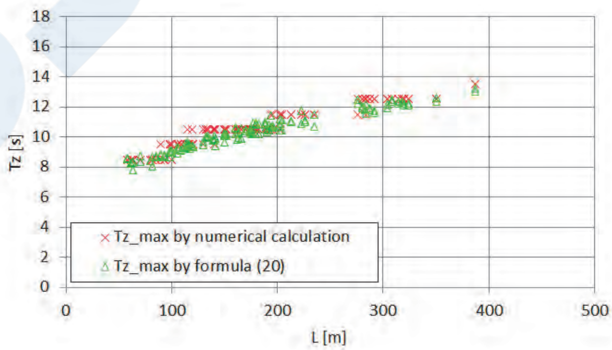
From Fig. 8, it can be seen that T_{z_max} tends to be longer than T_{z_BSR}. This is because, the significant wave height is considered in T_{z_max} but not in T_{z_BSR}. In order to convert T_{z_BSR} into T_{z_max}, the coefficient is determined by the relationship shown in Fig. 8 is expressed by using the water plane area LBC_w and the wave period in the most severe short-term sea state is expressed as in equation (20).

$$\begin{aligned} &\text{Heave acceleration} \quad && T_{z\_max} = 6.20(LBC_w)^{-0.16}T_{z\_BSR} \\ &\text{Pitch angle} \quad && T_{z\_max} = 3.67(LBC_w)^{-0.13}T_{z\_BSR} \end{aligned} \tag{20}$$

Figure 9 shows a comparison between equation (20) and the zero-up cross mean wave period for the most severe short-term sea state T_{z_max} obtained by the numerical calculation. As can be seen, the zero-up cross mean wave period in the most severe short-term sea state can be estimated with high accuracy by the conversion.



(A) Heave Acceleration



(B) Pitch Angle

Figure 9 Wave period (equation (20) and numerical calculation results)

8. WAVE FREQUENCY

As can be seen from equation (18), (19) and (20), in order to obtain T_{z_max}, the wave frequency $\omega_{RAOpeak}$ at which RAO is maximized is required. The RAO of the heave acceleration reaches its maximum value when the peaks of both the wave spectrum and the RAO are superimposed at the same wave frequency. When the RAO of the heave acceleration reaches its maximum value in a wave direction of 90 degrees, this maximum value becomes extremely large, whereas the sum $-{\omega_e}^2(M_{33}+A_{33})+C_{33}$ of the inertia term (mass and heave added mass) and the buoyancy term (heave restoring force coefficient) tends to be almost 0. Therefore, the $\omega_{RAOpeak}$ of heave acceleration is the wave frequency when the sum of the inertia term and the buoyancy term becomes 0, and is expressed as shown in equation (21). Equation (21) is based on the simplified formula of hydrodynamic coefficient by Matsui et al. [9]. As shown in Fig. 10, a comparison of the $\omega_{RAOpeak}$ values for heave acceleration obtained from equation (21) and from numerical calculation results indicates that the accuracy of the equation (21) is high.

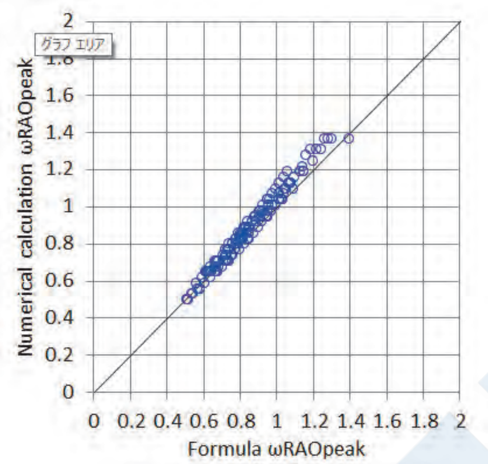


Figure 10　Comparison of $\omega_{RAOpeak}$ of heave acceleration between equation (21) and numerical calculation

On the other hand, when the wave direction is 180 degrees, the RAO of the pitch angle does not reach its maximum value when the peaks of both the wave spectrum with a mean wave period and the RAO are superimposed at the same wave frequency. The method used to obtain the $\omega_{RAOpeak}$ value for heave acceleration cannot be used. Therefore, based on the qualitative idea that $\omega_{RAOpeak}$ of the pitch angle does not depend on the ship length, when the $\omega_{RAOpeak}$ obtained from numerical calculation is non-dimensionalized by the ship length, the non-dimensional values of the $\omega_{RAOpeak}$ were expressed as Fig. 11.

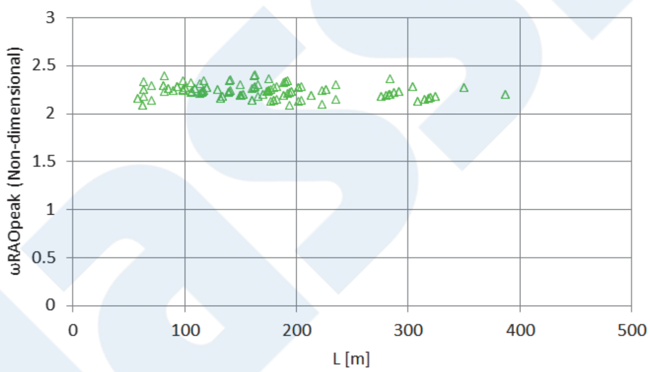


Figure 11　Non-dimensional $\omega_{RAOpeak}$ of pitch angle of numerical calculation

From Fig. 11, it was able to be seen that the non-dimensional $\omega_{RAOpeak}$ of the pitch angle is almost constant regardless of the ship length. From this reason, the non-dimensional $\omega_{RAOpeak}$ was determined as 2.23, and the $\omega_{RAOpeak}$ was determined as in equation (21).

Heave acceleration

$$\omega_{RAOpeak} = \sqrt{\frac{gC_w}{dC_b + 0.108\pi B \frac{2C_w{}^2}{C_w + 1}}} \tag{21}$$

Pitch angle

$$\omega_{RAOpeak} = 2.23\sqrt{\frac{g}{L}}$$

As shown in Fig. 12, the $\omega_{RAOpeak}$ values for pitch angle obtained from equation (21) and from numerical calculation results were compared. The $\omega_{RAOpeak}$ was able to set relatively high-precision formula.

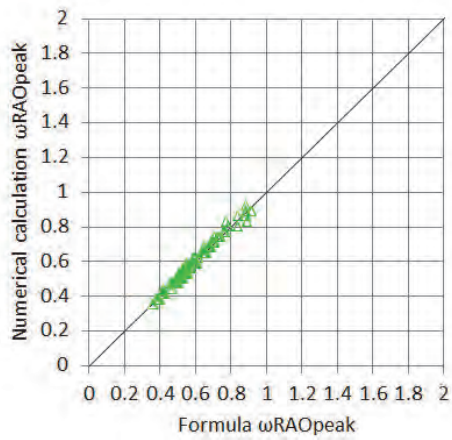
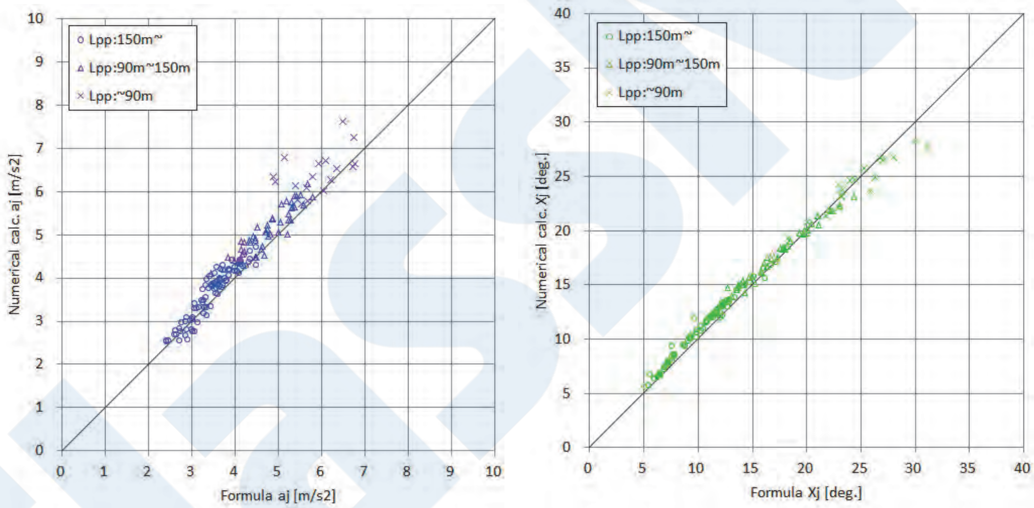


Figure 12　Comparison of $\omega_{RAOpeak}$ of pitch angle between equation (21) and numerical calculation

9.　COMPARISON OF CLOSED FORMULA AND NUMERICAL CALCULATION

Figure 13 compares the long-term predicted values with an exceedance probability of 10^{-8} for the heave acceleration and pitch angle values obtained from equation (4) to the numerical calculation results. As can be seen, the accuracy of the closed formula is high.



(A) Heave Acceleration　　　　(B) Pitch Angle

Figure 13　Long-term predicted values of exceedance probability of 10^{-8} (equation (4) and numerical calculation results)

10.　CONCLUSION

Highly accurate closed formulae of long-term prediction for heave acceleration and pitch angle were developed based on linear theory. The components of this proposed formula were introduced in Fig. 1. The components were briefly described as follows.

- Assuming the standard deviation in most severe short-term sea state of hull response has correlation with the peak RAO value, the value was used in order to formulate a long-term prediction. In this paper, RAO values obtained from numerical calculations in order to confirm proposed formulae was used; they were not formulated.
- Coefficients to convert from the peak value of RAO into standard deviation were formulated for each response using the water plane area LBC_w from qualitative hull motion phenomenon. (Sec. 5.1)
- Coefficients to convert from long-crested irregular waves into short-crested irregular waves were constant values for each

response. (Sec. 5.2)

- Standard deviation per unit significant wave height in the most severe short-term sea state was formulated by multiplying the coefficients of Sec. 5.1 and 5.2. (Sec. 5)
- Wave frequency of heave acceleration at which RAO is maximized was formulated from values when both the sum of the inertia term and the buoyancy term become 0. Wave frequency of pitch angle was formulated from the non-dimensional $\omega_{RAOpeak}$ based on the qualitative idea that $\omega_{RAOpeak}$ of the pitch angle does not depend on the ship length. (Sec. 8)
- Zero-up cross mean wave periods in the most severe short-term sea state were formulated based on the extremum of wave spectrum, so-called “broad sense of resonance” [14) 15)], and correction factors were determined by using the water plane area LBC_w for heave acceleration and pitch angle respectively. (Sec. 7)
- Significant wave height of an exceedance probability of 10^{-5} was formulated by using a joint probability distribution as a probability model for significant wave height and zero-up cross mean wave period. (Sec. 6)
- Maximum load with an exceedance probability of 10^{-8} was formulated by using most severe short-term sea state theory6). (Sec. 4)

As described above, the closed formulae presented in this paper were based upon RAO values obtained from numerical calculations. It is planned to use the closed formulae of the RAO developed based upon the theory of seakeeping analysis by author et al. Moreover, there are plans to develop closed formulae for lateral motions and bending moments following the same approach used in this paper.

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Climate Change Initiatives for Reduction of Greenhouse Gases

Sadao AKAHOSHI*

1. INTRODUCTION

The Paris Agreement, which is an international framework for the prevention of global warming, states that many of the effects of climate change can be avoided by limiting global warming to 1.5°C in comparison with the pre-industrial level. To achieve this, it will be necessary to reduce greenhouse gas (GHG) emissions by 45% by 2030 and achieve net zero emissions by around 2050, and over the 21st century, it will also be necessary to remove 100 to 1,000 gigatons of carbon dioxide (Gt-CO_2) from the air (carbon dioxide removal: removal of CO_2 in the atmosphere by biomass, CCS, etc. and permanent storage underground or in oceans, i.e., in deep ocean waters or the seabed). However, large-scale carbon dioxide removal technologies have not yet been applied practically. In order to avoid this, it is necessary to reduce CO_2 emissions at the earliest possible time so as to limit increases in CO_2 accumulating in the atmosphere.

Considering this situation, an increasing number of countries, centering on the advanced nations, have set targets for achieving net zero GHG emissions between 2050 and 2060, and the respective governments have announced GHG reduction targets for 2030 as milestones for achieving their long-term targets. As its target for 2030, Japan has set an emission reduction of 46% in comparison with 2013. (Table 1)

Table 1 GHG emission targets of main nations

	2030 interim target	Long-term target
UK	Minimum ▲68% (vs. 1990) (equivalent to ▲55.2% vs. 2013)	2050: Minimum ▲ 100% (vs. 1990)
Germany	▲65% (vs. 1990)	2045: Net zero emissions
EU	Minimum ▲55% (vs. 1990) (equivalent to▲ 44% vs. 2013)	2050: Net zero emissions
US	▲50-52% (vs. 2005) (equivalent to ▲45-47% vs. 2013)	2050: Net zero emissions
Japan	▲46% (vs. 2013)	2050: Net zero emissions
China	The amount of yearly emissions will be changed to decrease by 2030. (Reduction of per-GDP emissions exceeding 65% vs. 2005)	2060: Net zero emissions

Although none of these targets can be achieved easily, among the targets, the United Kingdom has set a particularly prominent target, as the UK will serve as the presiding country of COP26 in November 2021 and is strongly promoting the introduction of renewable energy, including successive development of large-scale wind power projects. In May of 2021, Germany announced that it will also raise its emission reduction target to a similar level. While both the EU and the United States are targeting reductions of more than 50%, it may be noted that the EU target is set against 1990, the baseline year of the Kyoto Protocol, while the United States sets its target against 2005, which was a year with large emissions. Japan's target of a 46% reduction against 2013 is similar to the levels of the EU and US if the targets of each country are compared against 2013. Moreover, since China is the world's largest GHG emitter (approximately 28% according to data for 2017 [1)]), an announcement of a target on this level, even if somewhat more modest, would have an incalculable impact.

Although these are targets at the national government level, on a private-sector base, various international activities called "climate change initiatives" are underway with the aim of encouraging advanced efforts for GHG reduction. Many of these are

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initiatives in which an environmental NGO has begun education and promotion of voluntary efforts by the private sector. However, since an increasing number of institutional investors and banks also support these activities, and a recognition that addressing climate change will have a large impact on financing and business operations as such is now well-established on the company side, a growing number of companies are responding proactively to these climate change initiatives.

Participation in climate change initiatives can be considered to be a commitment to business partners and the market; it means shouldering the responsibility of making efforts to reduce emissions over the long term, and measuring, reporting and announcing the results. Because emission reductions of the levels now under discussion will incur an significant cost increase for companies, if an equal footing of competitive conditions at the national level assumes the creation of a carbon border adjustment mechanism (CBAM: a mechanism by which a “carbon price” is imposed on imports from countries with inadequate climate change measures, corresponding to the amount of carbon emitted in the production process, so that those imports bear responsibility for emissions on the same level as in the importing country), there is a view that these climate change initiatives are actions at the private-sector level preceding international agreements. On the other hand, they also have the effect of showing the public and other concerned parties a company has adopted a stance of grappling earnestly with the issue of climate change.

This paper presents an overview of the main climate change initiatives, which have an increasing presence, and introduces consulting work on responding to climate change initiatives by our department during the past year.

2. MAIN INTERNATIONAL CLIMATE CHANGE INITIATIVES

2.1 CDP

2.1.1 Overview of CDP

CDP [2] was formerly known as the Carbon Disclosure Project. The organization originally conducted questionnaire surveys of companies on measures related to climate change and disclosed the results to investors and others, but began conducting surveys on water security in 2010 and on forests in 2012. Due to this enlarged scope, it changed its name to CDP (the initial letters of the original name) and is no longer called the Carbon Disclosure Project. It is an international NGO with headquartered in the UK.

The system of the CDP is as follows. Based on a request from an investor or a customer in a company’s supply chain, the CDP Secretariat asks the company to respond to a questionnaire. The company receiving the request responds voluntarily, selecting either “Public response” or “Non-public response.” Public response means the content of the response is posted on the CDP website, and when non-public response is selected, the response is only shared between the customer and the investor that requested the disclosure.

The contents of responses are scored by companies that act as CDP “scoring partners” based on a uniform scoring standard, and the results are released in 8 levels.

As mentioned above, responses are voluntary, but companies which choose not to respond are listed as “No response” or “Declined to participate” and given an evaluation of “F.” This evaluation means that the company did not provide sufficient information to be evaluated, and is not a reflection of the company’s environmental stewardship. (Fig. 1)

Figure 1 CDP scoring and evaluation system

As of 2020, the CDP had received responses from more than 9,600 companies at the request of more than 515 investors with assets in excess of US$106 trillion and 150 supply chain program members with purchasing power exceeding US$4 trillion. The responding companies accounted for more than 50% of world aggregate market value. Among Japanese companies, 801 companies responded to the questionnaire on climate change alone in 2020. Here, it may be noted that payment of a fee in the range of ¥100,000 to ¥700,000 is required when responding to the questionnaire.

Although the CDP requests disclosure of the climate change measures of companies for investors and customers, focusing mainly on determining the company's business continuity and growth potential, the content required in the response has a strong coloration of inducing action against climate change, as it heightens a company's awareness of climate change measures and encourages management improvements and efforts made at the company's own initiative. While it goes without saying that scoring is fact-based, the quality of the response will also affect the score. For this reason, it is essential to prepare responses based on an understanding of the intention of the questions and the complex evaluation system.

2.1.2 Main Elements in Response to CDP (Climate Change)

(1) Governance

In responding to the CDP questionnaire, it is necessary to explain whether board-level oversight has been established for climate change measures, the details of oversight by the board, the highest-level management position(s) with responsibility for climate-related issues, etc. Respondents are also asked whether there are incentives for the management of climate-related issues.

(2) Risks and opportunities

This is one of the central parts of the response. It is necessary to explain the processes for identifying, assessing and responding to climate-related risks and opportunities. In particular, respondents are asked to explain the identification of potential risks and opportunities specific to the company with the potential to have a substantial financial or strategic impact on the company's business, including the results of quantitative evaluations.

(3) Business strategy

The content of this section encourages adoption of the TCFD technique (Task Force on Climate-related Financial Disclosures; see section 2.3). For example, the respondent is asked whether the company uses a climate-related scenario analysis to establish its business strategy, and even if it is not currently using this type of analysis, a higher score can be obtained by indicating that it plans to implement this process in the future.

(4) Emission targets and performance, and calculations

The responding company is required to explain whether GHG emission reduction targets are set for the said reporting year, classified in the following 3 emission scopes (categories), and the specific initiatives for emission reduction and their quantitative effects. (Fig. 2)

Scope 1 emissions:

Amount of greenhouse gas emissions discharged directly by the company itself as a result of combustion of fuels, discharges in industrial processes, business activities, etc.

Scope 2 emissions:

Amount of indirect emissions of greenhouse gases accompanying the use of purchased energy, that is, electricity, heat and steam supplied from outside the company (equivalent to the GHG discharged at the sites where these forms of energy were generated).

Scope 3 emissions:

Amount of other indirect emissions, that is, emissions by other companies in the supply chain (value chain) related to the company's business activities (classified into 15 types).

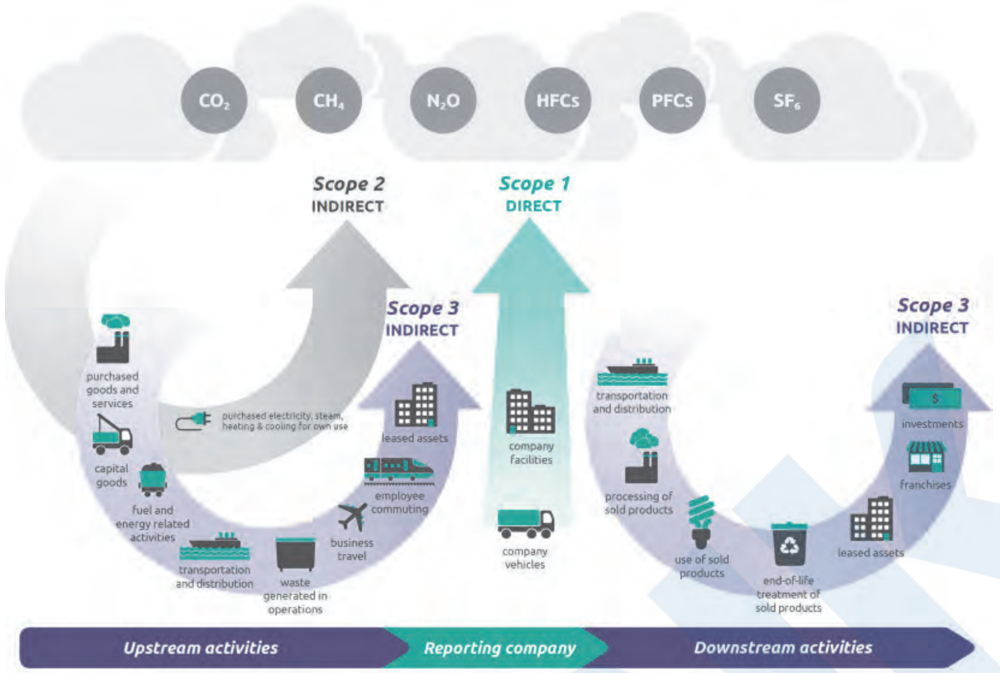

Figure 2　Classification of emissions by Scope
(Source: Corporate Value Chain Accounting Reporting Standard [3)])

Supplement on Scopes 1, 2 and 3: Example of Automobiles

The national government and local governments have announced policies under which internal combustion engine (ICE) automobiles (including both gasoline and diesel vehicles) manufactured and sold in this country will be replaced successively with electric vehicles (EV) in the future, and economic circles are now also involved in this discussion. From the viewpoint of CO_2 emissions, the change from ICE to EV is equivalent to a change from Scope 1 emissions (direct emissions) to Scope 2 (emissions generated from purchased energy).

As reference, according to a trial calculation of CO_2 emissions during travel of an ICE automobile and an EV, assuming the fuel consumption of the ICE vehicle is 15 km/*l*-gasoline, the CO_2 emission (Scope 1) is 155 g/km. On the other hand, assuming the electric power consumption of the EV is 0.1 kWh/km, when electricity charged from electric power generated by the electric utility company in Japan is used, the CO_2 emission (Scope 2) is 47 g/km. Thus, limited to CO_2 emissions accompanying travel, CO_2 is greatly reduced, even though the current composition of power sources is mainly thermal power. However, in the case of EVs, CO_2 emissions in the battery manufacturing process (equivalent to Scope 3 emissions) exceed those of ICE automobiles. Therefore, assuming the current power source composition, the CO_2 emission reduction effect of EVs may be limited if EVs are not driven long distances.

Accordingly, in addition to securing a supply of electric power for vehicle charging, the key to electrification of automobiles may be how much it is possible to increase renewable electricity and other power sources that do not directly produce CO_2 emissions.

Regarding Scope 2 emissions, although CDP recognizes renewable energy certificates (RECs), care is necessary when using offset credits, which are recognized under Japan’s Act on Promotion of Global Warming Countermeasures and Energy Conservation Law but are not recognized by CDP. (“Offset credits” are transferrable instruments equivalent to the difference between the amount of emissions before project implementation (baseline) and after implementation.)

Target setting methods include the method of setting an absolute emissions target (total amount target) and the method of setting an emissions intensity target (unit target, i.e., emissions per unit of activity) as a standard for measuring progress.

In particular, setting an aggressive reduction is recommended when setting an emission reduction targets as an SBT (Science Based Target; see section 2.2), as additional points are given in this case.

When listing the calculated amounts of Scope 2 emissions, CDP has adopted a method in which emissions are listed as both location-based Scope 2 emissions (calculated using a general emission factor applied to the location of places of business, etc.)

and market-based Scope 2 emissions (calculated using emission factors based on individual contracts for purchases of renewable energy, low carbon electric power, etc.), and the GHG reduction efforts of companies are expressed by a numerical value based on the difference between the amounts of emissions by the two methods. (Fig. 3)

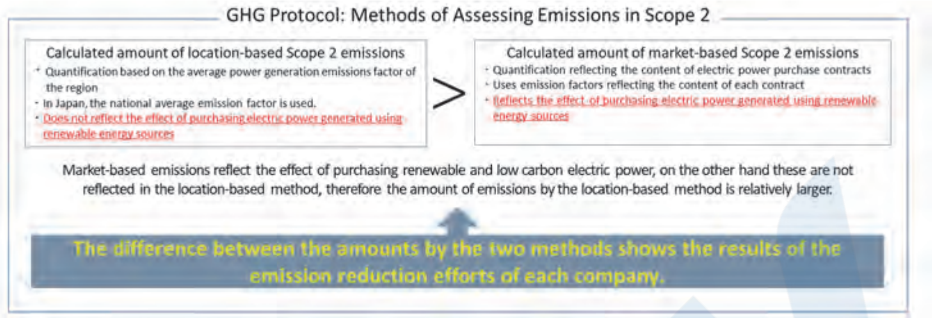

Figure 3 Comparison of location-based and market-based Scope 2 emissions

Furthermore, evaluations by CDP will differ, depending on whether the numerical amount of emissions is certified and guaranteed by a 3rd party organization or not.

It should be noted that an evaluation by CDP does not evaluate the absolute amount of GHGs, but rather, is an evaluation of how accurately the company has determined the amount of GHG emissions, whether it is currently making reduction efforts, and whether it has established a reduction plan for the future.

(5) Carbon pricing

Recently, the words “carbon pricing” have appeared frequently in newspapers. This expression generally means either a carbon tax or a “cap-and-trade” scheme consisting of some combination of upper limit regulations (“caps”) on total emissions and a system for trading emission permits (also called “emission credits” or “carbon credits”). A cap-and-trade system is called “carbon pricing” because a price is set for carbon credits, which are then bought and sold. In order to achieve the strict reduction targets mentioned in the Introduction, it appears that active discussion toward the full-scale introduction of this kind of economic system will also begin in Japan after the novel coronavirus problem has been solved.

In fact, Japan has already introduced a “global warming countermeasures tax” as a carbon tax in 2012, but its effect was extremely limited because the amount, ¥289/t-CO_2 was very low in comparison with other countries. (Fig. 4)

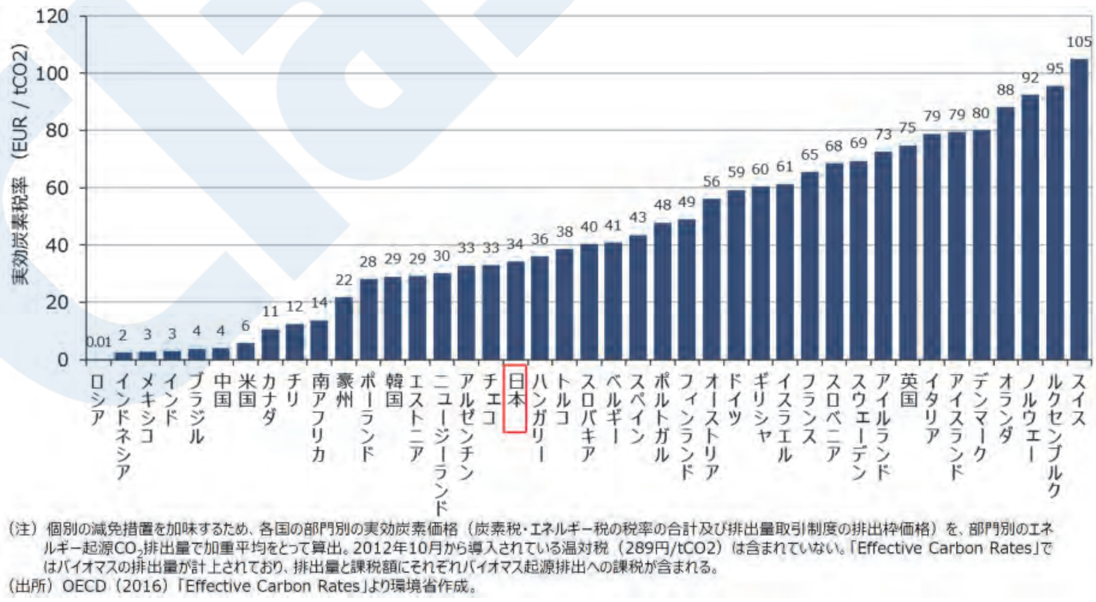

Figure 4 International comparison of effective carbon prices (all sectors; April 2012)
Total of tradable emission permit prices, carbon taxes and specific taxes on energy use
(Source: Materials of the 4th Meeting of the Subcommittee on Utilization of Carbon Pricing, Central Environment Council, Ministry of the Environment (Material No. 2)

On the other hand, independent cap-and-trade schemes have already been introduced in Tokyo and Saitama Prefecture, Japan and are contributing to reduction of CO_2 emissions in commercial buildings and manufacturing plants. Incidentally, because the European countries have successively announced strict interim targets to be achieved by around 2030, targeting net zero emissions in 2050, demand by companies that wish to acquire emission permits has led to active emission permit trading by hedge funds, causing a rise in trading prices. As a result, the trading market price rose from €20-30/ t-CO_2 in 2020 to €40/ t-CO_2 as of April 2021 (about ¥5,000 in Japanese yen). Trading prices are also expected to rise in the future in response to stricter regulations, and it appears that this will lead to more active discussion of a carbon border adjustment mechanism (CBAM).

With this lengthy preface, when responding to a CDP request, it is necessary to describe how the existing carbon pricing systems will impact your company's business. The CDP questionnaire also includes questions on the future rise in the carbon price called "internal carbon pricing," that is, whether the company is making efforts to use internal carbon pricing in investment decisions by setting virtual internal carbon prices in preparation against stronger regulations and increases in the actual carbon tax rate.

Depending on how it is used, the introduction of internal carbon pricing may become a factor that limits a company's competitiveness. However, many Japanese companies currently use internal carbon pricing for purposes such as encouraging low carbon investment, promoting energy conservation, and reform of internal behavior [4].

(6) Engagement

The suitable Japanese equivalent for "engagement" might be translated as "proactive collaboration." Here, "engagement" refers to countermeasures against climate change which are undertaken through proactive collaboration with suppliers and customers. The CDP questionnaire also includes questions on engagement such as "activities that could either directly or indirectly influence public policy" (e.g., related activities of trade associations). It is necessary to describe the details of these activities.

2.1.3 Status of Response and Evaluation of Japanese Companies, Etc.

Section 2.1.1 explained that responding companies are evaluated in 8 levels. In 2020, 5% of all companies received the A rank, which is the highest evaluation, in the field of climate change. This was a total of 273 companies worldwide, and included 53 Japanese companies. As these numbers suggest, Japan produces a large number of A rank companies, even from the global perspective.

In comparison with other countries, Japan has a low renewable energy introduction rate, and has even received a satirical award called the "Fossil of the Day" award for its continuing fossil fuel use. Thus, in light of this global direction in evaluations, it can be surmised that great effort was necessary by Japan's A rank companies to receive this positive evaluation.

2.2 Science Based Targets

Science Based Targets (SBT) is an initiative launched in 2015 to certify whether the GHG reduction targets set by companies are in line with the scientific knowledge of climate science recognized in the goals of the Paris Agreement (IPCC: Intergovernmental Panel on Climate Change). The managing organization, SBT, was established by a partnership of organizations promoting disclosure of climate change-related information, including the United Nations Global Compact (UNCG), the above-mentioned CDP, the World Resources Institute (WRI) and the World Wide Fund for Nature (WWF).

In order to participate in the SBT and receive examination of its GHG reduction targets, a company must set targets that cover a period from a minimum of 5 years to a maximum of 15 years. Setting of long-term targets that exceed 15 years is recommended.

In setting SBT, that is, reduction targets in line with the knowledge of climate science, the following items are necessary [5].

2.2.1 Scope 1 and Scope 2 Emissions

Targets should cover at least 95% of Scope 1 and Scope 2 emissions.

In principle, these targets are absolute reduction targets. However, depending on the business sector, a calculation method based on the special features of the sector (SDA: Sectoral Decarbonization Approach) is also acceptable, and in this case, setting of intensity targets (unit emission reductions per designated amount of production or activity) may also be recognized. The SBT's "SDA Transport Tool", which is based on the absolute reduction methodology, provides reduction scenarios, but at present, further development work is in progress.

Regarding the concrete reduction levels, prior to October 15, 2019, setting of targets for around 2025-2030, aiming at a reduction of 49% to 72% in 2050 was required, as this was considered to be the level of GHG emissions necessary to limit the average global temperature increase to less than 2°C. However, based on the IPCC Special Report on Global Warming of 1.5°C, targets should now be aligned with a pathway that limits the increase in global temperatures to “well below 2°C” as a minimum requirement, and efforts to achieve “targets that limit the temperature increase to 1.5°C or less” are recommended. (Fig. 5)

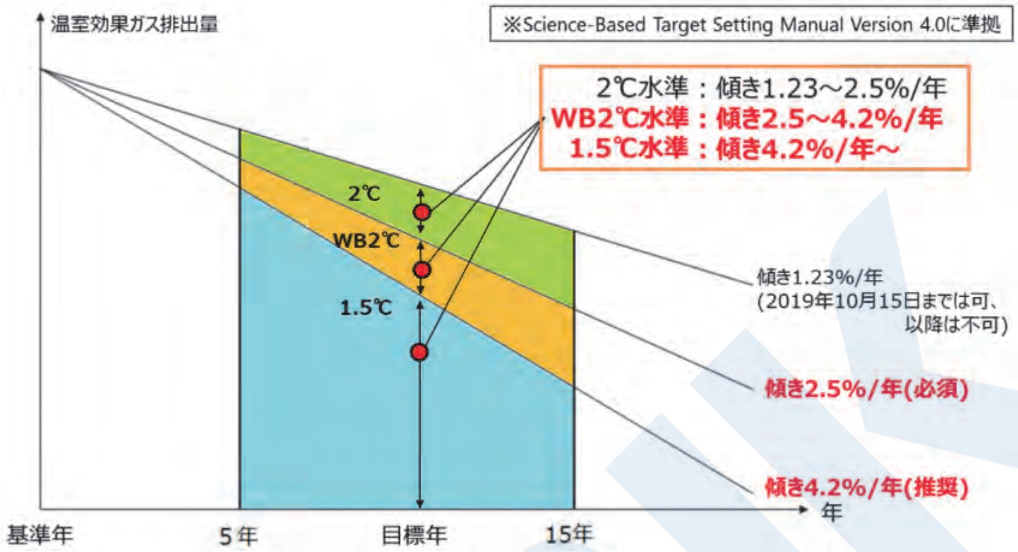

Figure 5　Image of reduction scenarios proposed by SBT
Source: Guidance for Encouraging Japanese Companies to Address International Initiative on Climate Change, Ministry of Economy, Trade and Industry (METI) / Ministry of Environment (March 2019; final revision, March 2021)

SBT also provides a method called Greenhouse Gas Emissions per Value Added (GEVA), which is suitable for fast-growing companies that provide various goods and services. In this case, a 7%/year compounded reduction is required.

As another alternative, limited to Scope 2 emissions, companies can set targets for procurement of electric power generated by renewable energy sources, provided those targets are in line with procurement of 80% of electricity from renewable sources by 2025 and 100% by 2030.

2.2.2　Scope 3 Emissions

A target for Scope 3 emissions should also be set if Scope 3 emissions account for at least 40% of total emissions (Scope 1 + 2 + 3 emissions). Reductions can be set as absolute emissions or as emissions intensity targets. These targets are considered “ambitious” if they lead to reductions in absolute emissions or emissions intensity that limit temperature increase to 1.5°C, well below 2°C or 2°C pathways, or if they are modeled by sector-specific methods approved by SDA.

Otherwise, physical intensity targets are considered ambitious if they reduce emissions intensity by an average of at least 2% per year over the target period. Economic intensity targets are deemed to be ambitious if they reduce unit emission reductions per value added by an average of 7% per year.

The boundary for all Scope 3 targets should include 2/3 of all Scope 3 emissions.

2.2.3　Status of Target Setting by Japanese Companies

As of May 7, 2021, 1,408 companies (including 129 Japanese companies) had officially committed to setting SBTs, and the targets of 701 companies (including 99 Japanese companies) had been recognized as complying with SBT requirements. In addition, 538 companies (including 20 Japanese companies) had pledged to set 1.5°C-aligned emission reduction targets under the SBT’s Business Ambition for 1.5°C program [6].

2.3　Task Force on Climate-related Financial Disclosures

The Task Force on Climate-related Financial Disclosures (TCFD) is a scheme which are proposed in September 2015 by Mr. Mark Carney, who was then the Governor of the Bank of England and the Chair of the Financial Stability Board (consisting of the Governors of Central Banks and Finance Ministers of member countries), based on concerns that climate change may impair the stability of the financial system. The TCFD was set up under private-sector leadership by the FSB during the period of COP21, and presented recommendations on voluntary financial climate-related disclosures in its Final Report in June 2017. Among other items, the following three types of risk were mentioned:

① Physical risk: Direct impacts such as destruction of assets caused by extreme weather events such as floods, torrential rains, etc., and indirect impacts due to disruptions of global supply chains and depletion of resources.

② Legal risks (liability for compensation): Risk that parties who suffer loss due to climate change may seek to recover damages from other parties through litigation.

③ Transition risks: Risk due to reassessment of financial assets with large GHG emissions accompanying the transition to a lower-carbon economy.

Based on this, more than 2,000 organizations called "supporters" have approved the aims of the above-mentioned proposal, and from 2018, CDP revised its questionnaire in a form corresponding to the TCFD. An increasing number of Japanese companies have also declared support for this initiative. Japan now ranks first in the number of supporters, with a total of 388 companies as of May 6, 2021, exceeding both the United States and the United Kingdom [7]. Recently, there have also been remarkable moves toward establishment of regulations based on the TCFD recommendations.

The TCFD is a specialized disclosure framework for climate-related information which is different from disclosure frames like the Global Research Institute (GRI), which is tasked mainly with preparing sustainability reports concerning general ESG information for multiple stakeholders, and Integrated Reporting (IIRC), which similarly prepares comprehensive reports on general ESG information for investors.

The TCFD requires that all companies ① use climate scenarios with 2°C targets, etc. to ② assess climate-related risks and opportunities for their own company, ③ reflect the results in management strategy and risk management and ④ identify their financial impacts, and disclose this information in their general annual reports, etc. (Fig. 6)

Among non-financial sector groups, the TCFD provides supplemental guidance for four groups: ① Energy, ② Transportation, ③ Materials and Buildings and ④ Agriculture, Food and Forest Products.

[Supplemental Guidance for the Transportation Sector]

Types of industries: Aviation, maritime transportation, land transportation (rail, truck, vehicle)

Disclosure items: Disclosure related to the evaluation and potential impacts of financial risk to existing plants and equipment by stricter regulation and new technologies, and opportunities for investment in research and development of new technologies and use of new technologies to respond to low emission standards and regulations on fuel efficiency.

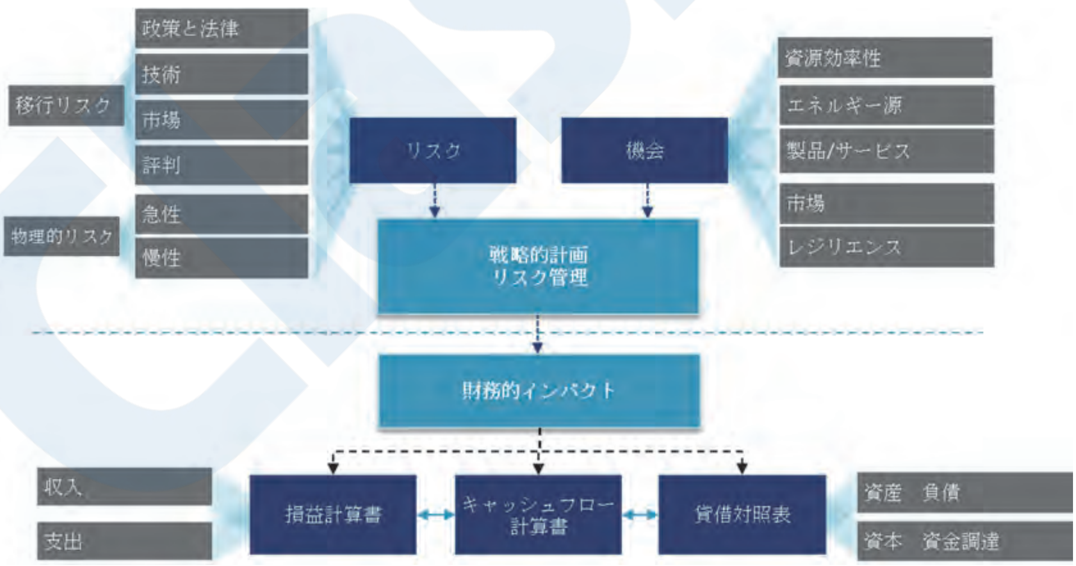

Figure 6　Climate-related risks, opportunities, and financial impacts

Source: Materials of explanatory meeting on "Final Report: Recommendations of the Task Force on Climate-related Financial Disclosures" [8] by the Financial Stability Board (July 2017)

The TCFD presents examples of the targets of disclosure for climate-related risks and opportunities and their financial impacts. Among the four basic disclosure items of the TCFD recommendations, namely, Governance which is most important, Strategy, Risk Management, and Metrics and Targets, explanations of "climate-related risks and opportunities" are required for each of these four items. (Table 2)

Table 2　TCFD requirements

Governance	Strategy	Risk Management	Metrics and Targets
Disclose the organization's governance around climate-related risks and opportunities.	Disclose the actual and potential impacts of climate-related risks and opportunities on the organization's businesses, strategy, and financial planning.	Disclose how the organization identifies, assesses, and manages climate-related risks.	Disclose the metrics and targets used to assess and manage relevant climate-related risks and opportunities.
Recommended Disclosures	Recommended Disclosures	Recommended Disclosures	Recommended Disclosures
a) Describe the board's oversight of climate-related risks and opportunities.	a) Describe the climate-related risks and opportunities the organization has identified over the short, medium, and long term.	a) Describe the organization's processes for identifying and assessing climate-related risks.	a) Disclose the metrics used by the organization to assess climate-related risks and opportunities in line with its strategy and risk management process.
b) Describe management's role in assessing climate-related risks and opportunities.	b) Describe the impact of climate-related risks and opportunities on the organization's businesses, strategy, and financial planning.	b) Describe the organization's processes for managing climate-related risks.	b) Disclose Scope 1, Scope 2, and, if appropriate, Scope 3 greenhouse gas (GHG) emissions, and the related risks.
	c) Describe the resilience of the organization's strategy, taking into consideration different climate-related scenarios, including a 2°C or lower scenario.	c) Describe how processes for identifying, assessing, and managing climate-related risks are integrated into the organization's overall risk management.	c) Describe the targets used by the organization to manage climate-related risks and opportunities and performance against targets.

Source: Materials of explanatory meeting on "Final Report: Recommendations of the Task Force on Climate-related Financial Disclosures" [8)] by the Financial Stability Board (July 2017)

When disclosing the above-mentioned items, the following "Principles for Effective Disclosures" should be observed.

① Disclosure should represent relevant information.
② Disclosures should be specific and complete.
③ Disclosures should be clear, balanced, and understandable.
④ Disclosures should be consistent over time.
⑤ Disclosures should be comparable between companies within a sector, industry, or portfolio.
⑥ Disclosures should be reliable, verifiable, and objective.
⑦ Disclosures should be presented on a timely basis.

2.4　RE100

RE100 (Renewable Energy 100%) is an international initiative which aims to switch the electric power used by companies in global business activities to 100% renewable energy by the year 2050. It was launched in 2014 by The Climate Group (an international environmental NGO headquartered in UK) in partnership with the CDP.

The targets for conversion to renewable energy under the RE100 initiative are as follows.

- All Scope 2 emissions related to the activities of the reporting company.
- Any Scope 1 emissions relating to the generation of electricity by the company.

- All companies operating within the brand or company group, including operations in which the brand or company group owns at least 50% of capital.
- Requirements for franchises and jointly owned companies (<50% of capital) will be assessed on a case by case basis.

As of April 2021, a total of 297 companies were participating worldwide, including 52 Japanese companies. In the case of the Japanese companies, the earliest target year for achievement of 100% renewable energy is 2025, and many are targeting 2050.

The target types of electric power are electricity generated from solar, wind, biomass, geothermal and hydropower (including large-scale hydropower) energy sources. (Note: As indicated by the name RE100, nuclear power is excluded from the targets.)

In addition to procurement of "real renewable energy" electricity, for example, by direct purchases of electric power actually generated by renewable energy power plants or installing photovoltaic (PV) panels on the roofs of the company's buildings, procurement of electric power generated from renewable energy sources also includes a menu of renewable electricity sold by electric power retailers, purchase of green power certificates, etc. Thus, companies whose CO_2 emissions are limited to electric power in service industries can also realize this requirement with relative ease.

As a feature of RE100, when renewable energy purchase methods are classified into the following two types, the merit of this initiative can be seen in the latter ②.

① Purchase of power generated by equipment originally existing in the grid or by equipment introduced under feed-in-tariff regulations.

② Installation of renewable energy power generating equipment with investment by the utility customer itself, and procurement of power generated by that equipment.

The above-mentioned ② is generally not easy. However, for companies with a comparatively large scale of business, installation of renewable energy generating equipment in the form of solar power or land-based windmills is still be considered easy in comparison with the construction of a thermal power plant or a large-scale hydropower plant.

There are also companies, exemplified by Apple, which have already achieved zero emissions associated with the electric power used by the company's own offices, direct sales outlets and data centers by purchasing renewable electricity, and are now requiring a zero emissions frame which also extends to their suppliers. For companies in Apple's supply chain, these moves to require the purchase of renewable electricity are a major challenge for business continuity, and there is also concern that this may become an Achilles heel for companies in Japan, where diffusion of renewable electricity has been delayed.

Incidentally, some companies in Japan have set voluntary evaluation criteria for procurement of electric power generated from renewable sources that exceed the requirements of RE100. For example, according to an announcement by Ricoh on March 2, 2021, the company has raised its renewable electricity target, and has also introduced a new comprehensive evaluation system to ensure the quality of domestic renewable electricity, including the purchase price, timing of installation of renewable electricity generating facilities, generating methods, the distance between the generating facility and the purchasing office or plant, etc. [9]. (Table 3)

Table 3 Total evaluation criteria for introduction of renewable electricity

Evaluation item (evaluation score)	High evaluation	Low evaluation
Purchase price of electric power (Prioritize lower cost renewable electricity)	Low price	High price
Additionality of equipment (Promote development of new renewable equipment)	New equipment	Existing equipment
Generation of CO_2 during power generation (Prioritize technologies with lower environmental impacts)	Solar / wind / hydropower	Biomass
Distance from power plant to user (Limit load on power grid)	Near	Far
Local company investment ratio (Contribution to local economy)	High	Low

3. EFFORTS BY ClassNK

As discussed in detail up to this point, in responding to climate change initiatives, a company must explain how it is making efforts in response to climate change initiatives in text and data form, based on the actual condition of the company and a thorough knowledge of the complex tools used by the various climate change initiatives.

On the occasion of consulting concerning the response to requests from CDP, which has the largest number of responding companies at present and includes a variety of initiatives, ClassNK plans to prepare a support menu for responding to the various climate change initiatives.

Figure 7　Steps in efforts by ClassNK (image)

First, ClassNK will prepare a step-by-step consulting menu in a form which is consistent with the Client's requests, targeting Clients in the marine transport and shipbuilding industries in which we have a detailed knowledge of global trends, etc. (Fig.7)

Based on this, we will promote a common correct understanding of the question system and scoring system of the CDP questionnaire by using easy-to-understand commentary materials prepared uniquely by ClassNK, and then provide support work for drafting a response which is clear, well-balanced and convincing. (Fig.8)

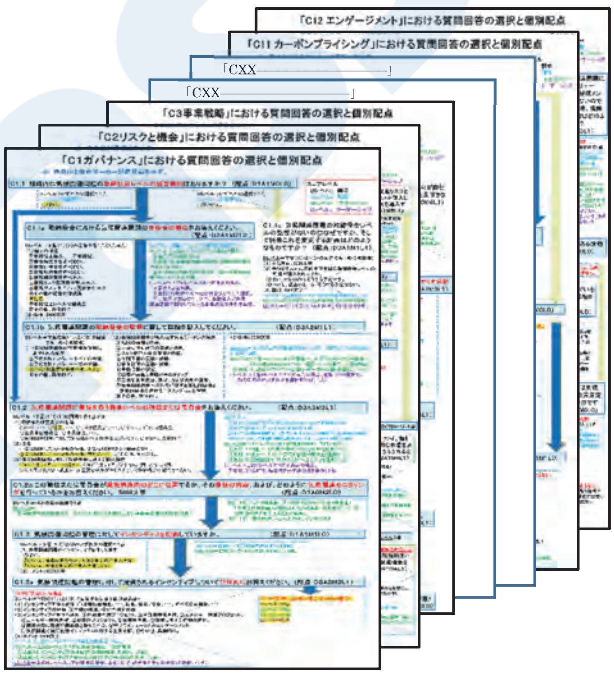

Figure 8　Original commentary materials prepared by ClassNK (Examples)

After the draft response is finished, the achieved level will be assessed by self-scoring, and Client can consult with ClassNK concerning its policy for the response (e.g., selection of information disclosure method, etc.)

Through this collaborative work with ClassNK, we hope to assist Client companies in developing policies on climate change countermeasures in each company.

4. CONCLUSION

All of the climate change initiatives introduced here originated in Europe. Since the dissemination of renewable energy has been delayed in Japan and the cost of renewable electricity is still high in comparison with Europe, and many Japanese industries and related companies are intrinsically energy-intensive, the author feels that some Japanese companies are adapting very skillfully to the rules of other countries.

On the other hand, in order to continue to respond successfully to increasingly strict GHG regulations in the future, social implementation of hydrogen and other clean fuels will be necessary for CO_2 reduction. As a general foundation, ClassNK has been involved in joint research and activities by various organizations, including efforts related to evaluation methods for other phases (production, storage, use) and the possibility of implementing life cycle analysis (LCA) of clean energy in addition to large quantity of transport for a long distance.

In any case, through the increasing opportunities to get together in various places in the future, we intend to consider the contributions that we can make, while continuing to exchange views with experts in all related fields.

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Efforts Related to “Innovation Endorsement”

Yoshimichi SASAKI*

1. INTRODUCTION

Accompanying progress in information technology, innovative initiatives have begun in a variety of fields, such as the auto mobile industry and the logistics industry. The maritime industry has also already started diverse efforts, exemplified by transfer of various types of data from ships to shore for condition-based monitoring of equipment and analysis of voyage optimization.

The main purpose of these efforts has so far included improvement in competitiveness for business efficiency, reduction in operation costs, and the creation of new data-driven value. However, addressing the issue of sustainable development has also become an additional motive force for innovation in recent years.

The Sustainable Development Goals (SDGs) laid out by the United Nations set 17 individual goals, including poverty, energy, growth, employment, climate change and marine resources. These SDGs define the future as the world should be in 2030, and are an image of the future which is supported by a global consensus. Realizing the SDGs will require new methods that might be different from the conventional procedures, including the use of information technology. It is not difficult to imagine that these kinds of innovations will give birth to new ideas that lead to a wider range of advances in the future.

Until now, classification societies have contributed to securing safety at sea and protecting the marine environment by evaluating whether ships comply with classification rules, international conventions, etc. Because classification societies possess this wealth of experience as third-party organizations, groups that are promoting innovation have called for certification and evaluation to further promote these efforts; however the lack of clear evaluation standards prevented us from fully meeting the needs.

With the aim of providing greater support for revitalization of the maritime industry and its surrounding industries, including initiatives for innovation, ClassNK announced the “ClassNK Digital Grand Design 2030,” which describes the roles that may be required of classification societies around the year 2030. As part of efforts to realize this vision, we have launched a new set of services called “Innovation Endorsement” for certification of innovative technologies and initiatives.

This article focuses on our efforts related to “Innovation Endorsement.”

2. CLASSNK DIGITAL GRAND DESIGN 2030

In innovative initiatives responding to advances in information technology and sustainable development, the creation of unprecedented value through collaboration among different players has begun, and the new players not bound by the conventional frameworks of individual companies have started to emerge.

Until now, ClassNK has supported the maritime industry to fairly and smoothly function by contributing to protection of the environment and human life, largely centering on three client groups: the shipbuilding industry, the maritime shipping industry and the insurance industry. However, the maritime industry has been going through a change with the number of new players such as the system integrators and digital forwarders increasing. As a result, the roles of each player in the maritime industry is assumed to change accordingly, resulting in that classification societies ourselves must also change in line with this dynamic industrial structure.

Therefore, based on the forecast of structural changes in the maritime industry by around 2030, ClassNK announced the “ClassNK Digital Grand Design 2030” in February of 2020, schematically summarizing new needs in digital transformation, the roles that may be expected of ship classification societies, and the contribution and services which this ClassNK should be provide in the maritime field and surrounding fields (Figure 1).

Specifically, to achieve the concept of “Creating Innovation for a Blue Economy,” the Digital Grand Design presents three

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roles which should be developed in the future along the axis of the conventional classification business: “Advanced surveys,” “Creating a progressive business environment”, and “3rd party certification, evaluation and rating.”

Figure 1　ClassNK Digital Grand Design 2030

3.　OVERVIEW OF “INNOVATION ENDORSEMENT”

With all companies making innovative efforts in response to the progress of information technology and to the issue of sustainable development, there is a heightened need for 3rd party certification of these technologies and efforts as well as ships that utilize the certification to emphasize diffusion and distinctiveness from other companies.

To meet this demand, ClassNK began a new certification scheme called “Innovation Endorsement,” as shown schematically in Figure 2.

Since proactive development of a certification service for innovative initiatives and the promotion of its popularization and growth will lead to further improvements in protection of the marine environment and safety at sea, and will also support sustainable development, it can be said that this is an effort by a certification organization to create new value based on “3rd party certification, evaluation and rating,” as proposed in the above-mentioned “ClassNK Digital Grand Design 2030.”

Figure 2　Schematic concept of Innovation Endorsement

Because innovative initiatives are the target of certification under the Innovation Endorsement program, the basic policy of this program was established as follows.

- Speed-focused: Since innovations progress rapidly, ClassNK will construct evaluation techniques and provide 3rd party certification services that prioritize speed synchronized to the pace of innovations.

- Cooperation with front-runners: In many cases, no evaluation criteria have been established for innovative efforts. Therefore, ClassNK will study and establish evaluation criteria in cooperation with front-runners who are the pioneers of innovative technologies.
- Certification required by clients and society: ClassNK will progressively expand the targets and the scopes of certification of innovative efforts based on clients’ requests and social conditions.

The target scope of certification is 4+1, that is, “Digital,” “Green,” “Safety,” “Labor” and “Yours.” In particular, “Yours” means addressing issues, requested for certifications by clients and society, that do not fit in any of the other four categories. When the Innovation Endorsement program was originally launched, the focus was innovative efforts utilizing digital technologies. However, since some efforts related to sustainable development do not necessarily utilize advanced digital technologies, “Green,” “Safety” and “Labor” were added to provide a scope of certification based on the purposes of innovations.

Concretely, the Innovation Endorsement program consists of three types of certification services which are performed individually: Notation service for ships, certification for Products & Solutions such as software and equipment, and certification for Providers of products and solutions. The following presents overviews of these three categories.

3.1 Notation Service

The object of certification is ships. The notations “DSS (Digital Smart Ship)” and “a-EA (advanced Environmental Awareness)” are added to the character of classification of ships that have made digitization initiatives and environmental initiatives. By including this information in the ship’s classification certificate, this service supports enhancement of added value of ships.

3.1.1 Digital Smart Ship

This is a service which certifies ships that have introduced innovations utilizing digital technology by adding the Digital Smart Ship Notation (abbreviated DSS) to the ship’s character of classification. The related guidelines, “Guidelines for Digital Smart Ships (First Edition)” were released at the end of August 2020.

The service specifies a framework for the notations for ship equipment and functions utilizing innovative technologies, which purpose is to support the introduction of innovative technologies and enhancement of added value of ships.

It is possible to add multiple symbols to the character of classification at once. To add symbols, ClassNK examines drawings and inspection records, and also conducts maintenance survey to confirm that the innovation has been put into operation and is being maintained.

In efforts related to innovative technologies, divisions of the levels of notation are also defined, assuming that more advanced technologies may be used in the future, even in functions for the same purpose, accompanying the progress of technology.

The current most recent edition, “Guidelines for Digital Smart Ships, Second Edition” (released in May 2021) includes the 10 items shown in Table 1 as innovations for which symbols will be added in the DSS Notation. For example, the Notation DSS(EE) for “energy efficiency” is added if a ship is equipped with a function that analyzes the operation data of the ship and uses the results to optimize fuel consumption on the next voyage.

Table 1 List of DSS Notation items

Item	Abbreviation	Outline
Energy Efficiency	EE	Fuel optimization
Hull Monitoring	HM	Hull monitoring
Sloshing	SLOSH	Sloshing detection
Machinery Monitoring	MM	Machinery condition-based monitoring (CBM)
Connected Ship	CNS	Onboard server, infrastructure, *etc*.
Navigation	NAV	Autonomous navigation equipment, *etc*.
Shore Monitoring	SM	Shore monitoring of equipment
Onboard Local Area Network	LAN	Onboard network
Refrigerated Cargo Shore Monitoring	RGSM	Shore monitoring of refrigerated cargos
Emission Shore Monitoring	ESM	Shore monitoring of emissions

Since various players are promoting innovations by diverse methods, DSS Notation items have been added in line with this trend. In the future as well, ClassNK plans to flexibly expand the items that can be added to the DSS Notation based on the needs of clients and conditions in the industry.

As of the end of May 2020, DSS Notations had been registered for about 70 ships.

3.1.2 Advanced Environmental Awareness

In 2009, ClassNK published an “Environmental Guideline” for addition of Environmental Awareness Notation (abbreviation: EA Notation) for ships that have introduced environmental technologies outperforming the requirements set out in international conventions.

With heightened awareness of Corporate Social Responsibility (CSR) and efforts to achieve the Sustainable Development Goals (SDGs), there have also been increasing efforts to voluntarily promote environmental technology beyond the framework of international conventions.

In order to support innovative efforts in connection with environmental countermeasures more quickly, the concept of “Innovation Endorsement” was incorporated in the Guideline from the Fourth Edition (May 2021), and this was added a “Client’s viewpoint” oriented service.

In this guideline, an Advanced Environmental Awareness Notation (abbreviated a-EA) is to be added to the list of notifications for ships that have made advanced environmental conservation efforts that go beyond the framework of international conventions and regulations.

In the 4th edition of the Environmental Guidelines, the seven initiatives that can be marked with Notation in the a-EA are listed in Table 2.

For example, a ship equipped with a bottom air lubrication system to improve propulsion performance will be marked with the Advanced Environmental Awareness (AIR LUBRICATION SYSTEM) abbreviation: a-EA (ALS) Notation.

Table 2 List of a-EA Notation items

Category 1	Category 2	Marks	Item
Air pollution Prevention	Reduction in Greenhouse Gas Emissions	SCELL-(PA)	Adoption of Solar Cell
		FCELL-(PA)	Adoption of Fuel Cell
		WINDG-(PA)	Adoption of Wind Generator
		ORCWHR-(PA)	Adoption of Wave Heat Recovery System with Low-Boiling Medium such as Organic Rankine Cycle Generator System
		EGWHR-(PA)	Adoption of Exhaust Gas Waste Heat Recovery System
Others	Propulsion Performance	ALS	Provision of Bottom Air Lubrication Systems
		ESA	Adoption of Energy Saving Additives

As is the case of the DSS Notation, efforts in connection with these environmental countermeasures are being promoted by diverse methods, so that ClassNK plans to continue expanding Advanced Environmental Awareness items quickly and flexibly based on the needs of clients and conditions in the industry.

3.2 Products & Solutions Certification

Products & Solutions certification is to promote the diffusion and further development of excellent products and solutions.

Among advanced products utilizing cutting-edge technologies, in this service, ClassNK issues certificates for functions for which the company developing a product requests 3rd party certification from the viewpoints of technical validity and safety, utilizing its know-how as a ship classification society to date.

In the future stage when we have collected results of certification for a number of similar solutions, we plan to document the evaluation criteria and evaluation procedures more concretely and develop guidelines for public release so as to heighten the transparency of certification. For example, we may collect results of certification for condition-based monitoring (CBM) solutions for engines.

The Products & Solutions certificate is truly a “fully-customizable” certificate. The certification process begins when

ClassNK receives a proposal by an applicant about “what” should be certified. This “what” will be listed as the “Product Description” in the certificate issued by ClassNK. Since there are no evaluation criteria for these proposed advanced functions in many cases, ClassNK studies the evaluation criteria together with the applicant, also utilizing its experience as a ship classification society until now. For example, in case the function of “remote monitoring” is to be certified, the items that should be confirmed for “remote monitoring” are decided through consultation in the certification process.

The certificate is then issued after a review of the manuals, specifications and other product documents related to the confirmation items and confirmation of operation.

As of the end of May 2021, issuance of 4 certificates had been completed, and ClassNK had received inquiries concerning about 20 products from Japan and other countries.

3.3 Provider Certification

Provider certification is a certification service that targets the initiatives and business models of companies.

The service aims for a “new form” of certification which supports enhancement of stakeholders’ mutual trust by 3rd party certification of innovation activities of organizations for target achievement in line with the SDGs and ESG (Environmental, Social and Governance) investing. To make the fullest possible use of certification as an immediately effective tool, ClassNK is examining certification in the following three classes.

In all stages of certification, the activities and results of the innovation-generating organizations are verified from the perspective of the management system.

- Class C: Certification of the concept of the organization that intends to implement innovation. We will examine verification of the policy, planning and organizing of innovation, e.g. "matrix of business activities," "two-story innovation management," "open innovation," etc.
- Class D: Certification of the ability of an organization with a Class C certificate to implement innovation. We will use specific examples to verify that innovation is carried out using the methods and tools necessary to the implementation of innovative activities. Examples are the "innovation compass", the "stage-gate method" and the "knowledge creation process," to name a few.
- Class S: It certifies that an organization with D level certification has implemented innovation and that the outcomes have been implemented in the business. It verifies that the organization has implemented innovation in a sustainable manner, for example in accordance with ISO 56002 guidelines.

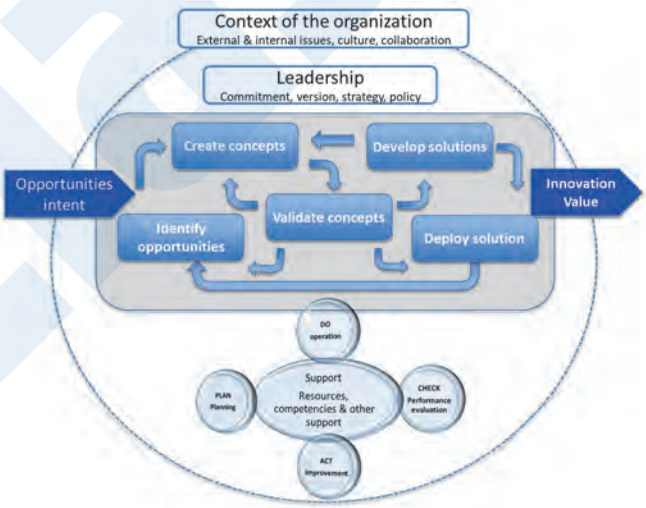

Figure 3　Framework of Innovation management system (images)

4. FUTURE DEVELOPMENT

As described above, the Innovation Endorsement program consists of 3 individual certifications services for the targets of certification, a Notation service, Products & Solutions certification, and Provider certification.

In the future, ClassNK plans to provide certification not only for methods and functions of utilizing innovative technologies but also for the client's effort itself.

For example, we are considering certifying the results of efforts related to ESG investing by companies, such as fuel consumption reduction results obtained by energy-saving technology and the length of downtime reduction achieved by condition monitoring technology (CBM etc.).

Since it is imperative to do indexing based on various evaluation axes for the certification of these results, we consider it necessary to have the consultation with all players including discussion on the feasibility.

5. CONCLUSION

"ClassNK Digital Grand Design 2030" mentions "3rd party certification, evaluation and rating" as one core business. In line with this, ClassNK began "Innovation Endorsement" to provide the tangible services, considering that one of the biggest roles that ship classification societies should play around 2030 is support for innovative technology and initiatives.

At present, Innovation Endorsement provides three certification services covering Notation, Products & Solutions and Providers, with a scope that includes use of digital technologies, protection of the environment, safety at sea and labor. In the future, Innovation Endorsement will also expand the scope of certification flexibly based on the new requests from clients and the change in social conditions.

Through Innovation Endorsement, ClassNK will proactively develop the new certification services demanded by clients and the industry, while continuing to utilize its knowledge as a ship classification society, in order to support the activities of Clients that aim for sustainable development through advanced initiatives.

Recent Topics at IMO

— Outline of Discussion at IMO Committees —

External Affairs Department, ClassNK

1. INTRODUCTION

This article introduces recent topics discussed at IMO (International Maritime Organization). At the previous issue, a summary of the topics discussed at 75th Marine Environment Protection Committee (MEPC 75) and 102nd Maritime Safety Committee (MSC 102) held in 2020 was provided.

This article provides a summary of the decisions taken at 103rd Maritime Safety Committee (MSC 103) held from 5 to 14 May 2021 as below. MSC 103 was held remotely in lieu of physical session at the headquarters of IMO, due to COVID-19 situation. Please bear in your mind that, since some relevant IMO Sub-Committee meetings were not held after MSC 102 and time constraints due to remote meeting, a number of proposals and comment papers were not considered at MSC 103 and thus postponed to MSC 104 to be held in October.

2. OUTCOMES OF MSC 103

2.1 Adopted Mandatory Requirements

Mandatory requirements were adopted at MSC 103 as follows:

(1) Water level detectors on multiple hold cargo ships

Amendments to SOLAS regulation II-I/25-1 to require water level detectors on multiple hold cargo ships other than bulk carriers and tankers for cargo holds located below the freeboard deck, and intended for dry cargoes.

(2) Amendments to SOLAS chapter III, LSA Code and resolution MSC.81(70)

Amendments to SOLAS regulation III/33, paragraph 4.4.1.3 of LSA Code and the “Revised recommendation on testing of life-saving appliances” (resolution MSC.81(70), as amended), to exclude free-fall lifeboats from the scope of application of the requirements to launch lifeboats with the cargo ship of 20,000GT and above making headway at speeds up to 5 knots in calm water. As for early implementation of the amendments to SOLAS chapter III and LSA Code, refer to below item 2.2.(2).

(3) Amendments to 2011 ESP Code

Amendments to 2011 ESP Code, which replace the provision of thickness measurements at the first renewal survey of double hull oil tankers.

(4) Amendments to chapter 9 of the FSS Code

Amendments to chapter 9 of the FSS Code in respect of fault isolation requirements for cargo ships and passenger ship cabin balconies fitted with individually identifiable fire detector systems.

2.2 Approved Guidelines etc.

The following guidelines etc. were approved at MSC 103.

(1) Amendments to the Guidelines for the maintenance and inspections of fixed carbon dioxide fire-extinguishing systems (MSC.1/Circ.1318)

Amendments to the Guidelines for the maintenance and inspections of fixed carbon dioxide fire-extinguishing systems (MSC.1/Circ.1318) were approved, aiming to clarify the hydrostatic testing regime for high-pressure CO2 cylinders.

(2) Early implementation Circular on the amendments to SOLAS chapter III and LSA Code

With regard to above item 2.1.(2), the Circular to urge Administrations’ early implementation on the amendments to SOLAS chapter III and LSA Code to exclude free-fall lifeboats from the scope of application of the requirements to launch lifeboats with the cargo ship of 20,000GT and above making headway at speeds up to 5 knots in calm water, was approved.

2.3 Consideration of Requirements for Maritime Autonomous Surface Ships (MASS)

Taking into account recent investigation of automation surrounding a ship, it has been discussed at MSC on conventional requirements of safety and environmental protection relating to MASS.

At this session, it was reported that the Regulatory Scoping Exercise (RSE) has been accomplished. In result of RSE, potential gaps between the current IMO instruments and requirements for MASS, and priorities for further work, were identified. In conclusion, it was agreed to consider a separate MASS instrument from existing IMO instruments.

2.4 Consideration of Safety Matters on Use of Low Sulphur Fuel

Triggered from the global 0.5% sulphur limit, which will enter into force on 1 January 2020, consideration of safety matters on use of low sulphur fuel was initiated, in order to develop SOLAS requirements in addition to requirements of MARPOL.

In conclusion at MSC 103, it was agreed to develop mandatory requirements and guidelines to address situations where the oil fuel supplied may not comply with SOLAS regulation II-2/4.2.1 at future sessions.