Research and Development on Ship Collisions

— Consideration of the Equivalent Added Mass Coefficient of a Struck Ship [*1] —

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1. INTRODUCTION

The Common Structural Rules of the International Association of Classification Societies (IACS) specify residual strength requirements for the accidental limit state of ships, considering loss of structural strength accompanying a collision or grounding, which require that a ship have sufficient hull strength to withstand waves and internal loads following a collision or grounding. Probabilistic risk assessments are necessary in the development and practical application of new concept ships loaded with new fuels such as hydrogen or ammonia, and evaluation of the collision/grounding resistance performance of ship fuel tanks and hull structures is important for this [1) 2)]. If an appropriate evaluation of collision/grounding resistance performance can be carried out, more rational design of the hull structure and flexible arrangement of the fuel tanks will become possible, while continuing to consider the risk of flooding and sinking and the risk of fuel leakage. Furthermore, when two ships collide, the scale of damage of the bow section of the striking ship and the hull of the struck ship varies depending on the ship motion accompanying the collision. Therefore, a coupled analysis of the ship motion (external dynamics) and the absorbed energy of the hull structure (internal mechanics) accompanying a collision is important for evaluating this phenomenon.

Several evaluation methods of this type of collision are available, but with recent progress in computer performance, Nonlinear Finite Element Analysis (NLFEA) is now generally used [3)]. In external dynamics, the effects of hydrodynamic forces (*e.g.*, added mass, *etc.*) associated with ship motion are frequently ignored or simplified to reduce the cost of the analysis. One simplification method is the Constant Added Mass Method (CAM method), in which a constant added mass is added to the ship's displacement mass and a whole ship collision and grounding analysis is carried out. Minorsky [4)] proposed an added mass coefficient of 0.4 for the sway motion of the struck ship during a collision. However, Motora *et al*. [5)] reported that the equivalent added mass coefficient of the struck ship (including the effect of the wave damping force) exceeds 0.4 as the duration of the collision becomes longer. In any case, rational and concrete values for the equivalent added mass coefficient which enable an appropriate evaluation of the effects of hydrodynamic forces (hydrodynamic effects) on the struck ship still have not been reported, and remain unclear.

Therefore, in this research, the authors examine an equivalent added mass coefficient which enables a proper evaluation of the hydrodynamic effects acting on a struck ship by analyzing the sway motion of the struck ship in a ship-ship collision of two fully-loaded VLCCs (Very Large Crude Carriers). If it is possible to derive an appropriate equivalent added mass coefficient for the struck ship, a simpler and more rational evaluation of collision resistance performance will become possible. The MCOL and S-ALE (Structured Arbitrary Lagrangian and Eulerian) fluid-structure interaction analysis methods packaged in the commercial NLFEA program LS-DYNA are used in this study.

2. OVERVIEW OF FLUID-STRUCTURE COUPLING METHODS FOR COLLISION ANALYSIS

2.1 MCOL

MCOL is a subprogram of LS-DYNA that can efficiently consider hydrodynamic effects in collision analyses by LS-DYNA [6)]. Concretely, it is possible to carry out collision analyses that consider the added mass, wave damping force (memory effect), restoring force (stability) and viscous force (drag) accompanying a collision. However, the added mass and wave damping

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coefficient must be calculated separately using an analysis program, *etc*. based on potential theory.

In MCOL, the following equation of motion is solved assuming that the ship's hull is a rigid body with 1 mass point and 6 degrees of freedom (6-DOF) [7].

$$[M + M_A][\ddot{x}] + [G][\dot{x}] \\ = [F_W(\dot{x})] + [F_H(x)] + [F_V(\dot{x})] + [F_C] \quad (1)$$

where, M and M_A are the displacement mass/inertia matrix of a ship and the added mass and inertia matrix for infinite frequency, respectively, G is the gyro matrix and F_W, F_H, F_V and F_C are the wave damping force (memory effect), restoring force, viscous force and contact force, respectively. In F_W, the memory effect is calculated by the following equation:

$$F_W = -\int_0^t [G(\tau)][\dot{x}(t-\tau) - \dot{x}(0)]d\tau \quad (2)$$

where,

$$G(\tau) = \frac{2}{\pi}\int_0^\infty [C(\omega)]\cos(\omega\tau)\,d\omega$$

$C(\omega)$ represents the wave damping coefficient matrix. The added mass/inertia matrix for infinite frequency and the wave damping coefficient matrix $C(\omega)$ in the frequency range of 0.02 to 2.38 rad/s (0.04 rad/s increments) were calculated using program of the 3-dimensional Green's function method. Because it is necessary to designate the values of the drag coefficient C_D in the viscous force term and, $C_D = 0.8$ (sway direction) was assumed in order to treat the VLCC [8].

2.2 S-ALE

The ALE method is a fluid-structure interaction analysis method, and is applicable to analyses of complex nonlinear phenomena such as collision analysis. To date, the ALE packaged in LS-DYNA has a proven record of use in research on ship collisions [9-11]. Recently, it has become possible to use the function called S-ALE, which achieved high efficiency in ALE. Due to the improved parallel performance of S-ALE, its computational speed is faster than that of the conventional ALE. S-ALE was used in this study. As in the conventional ALE, S-ALE models the structure and fluid by using Lagrangian elements and Eulerian elements, respectively.

Fig. 1 shows the models. Seawater and air were modeled as the fluids. Table 1 shows the values of the material properties (MAT) and equations of state (EOS) for seawater and air, which were decided referring to the literature [12]. Ambient elements were arranged over the full surface of the fluid, simulating an infinite domain field.

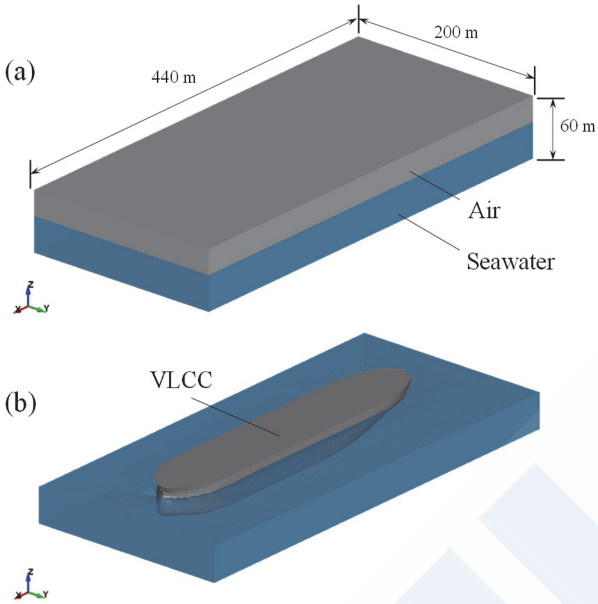


Fig. 1 FE-model for S-ALE: (a) dimensions of fluid domain; (b) VLCC which floats on fluid domain.

Table 1 Material properties for seawater and air.

Seawater		
*MAT NULL	Density, ρ (kg/m^3)	1025
	Pressure cutoff, P_c (Pa)	-100
	Viscosity coefficient, μ (Pa・s)	1.075×10^{-3}
*EOS GRUNEISEN	Nominal sound speed, C (m/s)	1500
	S1, S2, S3, GAMAO, A, E0	0.0
	V0 (-)	1.0
Air		
*MAT NULL	Density, ρ (kg/m^3)	1.1845
	Pressure cutoff, P_c (Pa)	-10
	Viscosity coefficient, μ (Pa・s)	1.850×10^{-5}
*EOS LINEAR POLYNOMIAL	C0, C1, C2, C3, C6	0.0
	C4, C5 (-)	0.4
	E0 (Pa)	2.533×10^{5}
	V0 (-)	1.0

2.3 Differences between MCOL and conventional ALE

Using MCOL and conventional ALE, Rudan *et al.* [11)] analyzed the sway velocity of an LPG ship in a collision by giving loads simulating the contact force during the accident to the ships, and compared the two methods. As a result, they reported that the sway velocity obtained by MCOL was larger than that by the conventional ALE. Drag calculations cannot be performed in a fluid analysis by the ALE in LS-DYNA, but drag can be considered easily by MCOL. Although this is a difference between the two programs, the actual reason for the difference between MCOL and ALE has not been clarified in detail. Therefore, we carried out a comparative verification by analyzing the sway velocity, contact force and absorbed energy of the struck ship

(VLCC) using the respective hydrodynamic effect evaluation methods (MCOL, S-ALE, and CAM method).

3. COLLISION ANALYSIS

3.1 Collision Scenario

As a dangerous collision scenario, a scenario in which the striking ship is as large or larger than the struck ship, and the kinetic energy of the striking ship is larger, is generally considered. Therefore, we assumed that the striking ship and the struck ship were identical, and both were in the fully-loaded condition. The principal particulars of the target ship (double-hulled VLCC) are shown in Table 2. The analysis conditions were set so that sway motion occurred in the struck ship, assuming that the centerline of the striking ship collides with the struck ship at right angles (90° angle) at its center of gravity position, as shown in Fig. 2. The speed of the striking ship was set to the 3 levels of 3, 6 or 9 knots, and the struck ship was in the stopped condition.

Table 2 Principal particulars of VLCC.

Dimensions	Value
Length, L_{oa} (m)	333
Length, L_{pp} (m)	324
Breadth, B (m)	60
Draft, d (m)	20.5
Displacement, Δ (ton)	3.418×10^5

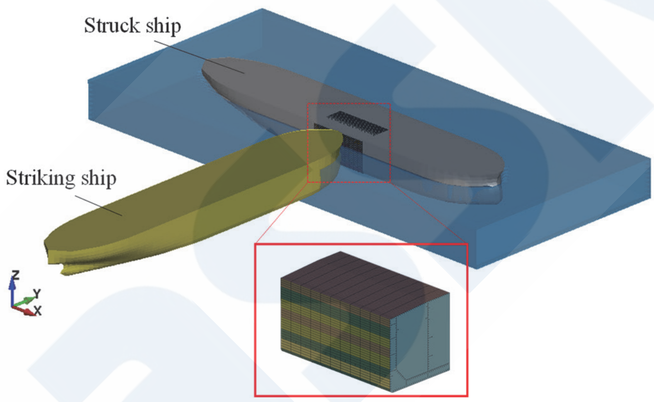


Fig. 2 FE-model for S-ALE between two ships in collision.

3.2 Analysis Model and Analysis Conditions

The NLFEA program LS-DYNA (ver. mpp d R12.0.0) was used in the analysis. Fig. 2 shows the FE model of the striking ship and struck ship when using S-ALE. The whole ship models (hull shape only) of the striking ship and the struck ship were both assumed to be rigid bodies (1 mass point, 6-DOF). The region around one longitudinal tank in the central part of the starboard side of the struck ship was modeled separately as an elastic-plastic body. The transverse bulkhead (rigid body) in the model of the ship's central starboard side was connected with the whole ship model (rigid body) by using *CONSTRAINED RIGID BODIES of LS-DYNA, which is used to connect pairs of rigid bodies, due to the analytical constraints on the fluid-structure interaction. Specifically, when using S-ALE, the sizes of the structural elements and the fluid elements must be substantially the same, but due to the extremely small element size of the elastic-plastic body (approximately 100 mm x 100 mm), use of fluid elements of the same small size would be impossible in terms of analysis cost. Therefore, the model of the central starboard side was connected to the whole ship model, in which a larger element size (approx. 4 m x 4 m) was applied, and only the whole ship model was coupled with the fluid elements, making it possible to conduct an efficient fluid-structure interaction analysis. Here, even though the elements of the whole ship model and the central starboard side model overlapped, a coupled evaluation of the external dynamics and internal mechanics in the collision analysis was possible by setting the model so that the bow of the striking ship only made contact with the struck ship's central starboard side model (and did not come into contact with the whole ship model). This approach has been used in conventional studies[10) 11)]. The analysis conditions of the striking ship and struck ship are summarized in Table 3. It may be noted that the element size of the whole ship model (approx. 4 m x 4 m) was determined by performing convergent calculations in S-ALE, while the element size of the ship's central starboard side (approx. 100 mm x 100 mm) was decided referring to the literature [13].

All members in the central starboard side model were prepared using shell elements (four-node Belytschko-Tsay elements). The total number of elements was approximately 2.64 million. Table 4 shows the material constants and other properties of the tank, which are based on the true stress-true strain curves. *MAT PIECE-WISE LINEAR PLASTICITY (024) of LS-DYNA was used as the material constitutive rule, and strain rate dependence was considered by using the Cowper-Symonds model. Rupture of the structure was expressed by removing elements when their equivalent plastic strain reached the critical failure strain shown in Table 4. The value of this failure strain was determined by referring to the past literature [13], considering the mesh size. The static/dynamic friction coefficients were set to 0.3. Because the purposes of this study were to carry out a relative comparison of the various hydrodynamic effect evaluation methods and study the equivalent added mass coefficient, the reader should note that simplified assumptions were used for the material constants, *etc*. of the elastic-plastic model described above.

Table 3 Analysis condition.

	Struck ship	Striking ship
Loading condition	Full	Full
Motion	6-DoF	Surge
Velocity (kt)	0.0	3.0, 6.0, 9.0
Hull (including bow)	Rigid	Rigid
Tank	Elasto-plastic	-
Coupling with fluid	Hull	-

Table 4 Material properties for the tank (true stress-strain) [13].

Steel grade	MS	HT32	HT36
Yield stress, σ_y (MPa)	235	315	355
Ultimate tensile stress, σ_u (MPa)	450	530	560
Critical failure strain, ε_{cr} (-)	0.20	0.167	0.15
Density, ρ (kg/m^3)	7850	7850	7850
Young's modulus, E (GPa)	206	206	206
Poisson's ratio, ν (-)	0.3	0.3	0.3
Tangent modulus, E_t (MPa)	1085	1303	1385
Strain rate parameter, C (-)	40.4	3200	3200
Strain rate parameter, P (-)	5.0	5.0	5.0

4. ANALYSIS RESULTS

4.1 Sway Velocity (Rigid Body)

As mentioned previously, it has been reported [11] that analyses by MCOL of LS-DYNA and the conventional ALE result in different sway velocity values. First, therefore, the sway velocity of only the whole ship model (rigid body, 1 mass point, 6-DOF) was analyzed using each of the hydrodynamic effect evaluation methods (MCOL, S-ALE CAM method), and the obtained results were analyzed. The target ships were moved by applying a load simulating the contact force during a collision (sine wave, duration of action: 5 s), as shown in Fig. 3, at the center of gravity of the struck ship in the sway direction. This load simulates the contact force obtained in the collision analysis when the forward (surge) velocity of the striking ship was 6 kt.

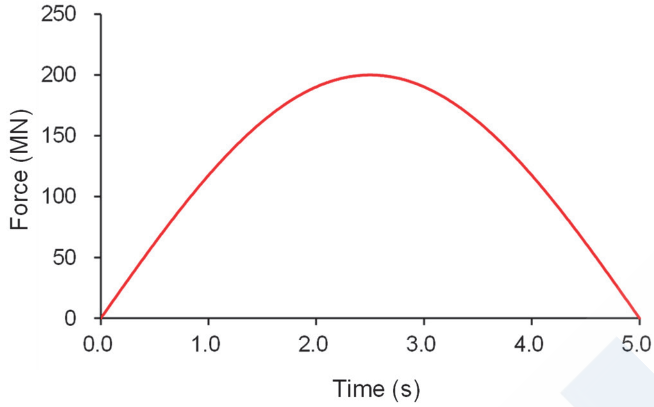


Fig. 3 Force assumed in sine wave similar to contact force during collision.

Fig. 4 shows the result of a comparison of the sway velocities obtained by each of the hydrodynamic effect evaluation methods. Good agreement between the results of the MCOL and S-ALE methods can be confirmed. Although it had been reported that the results by these two methods in the conventional study were not in agreement, the results were almost identical. Although the reason for the reported difference has not been clarified, it can be inferred that a difference in the ship types, *etc*. in the conventional study and this study was a factor. In addition, as noted previously, calculations for drag are not possible by the ALE of LS-DYNA (including S-ALE), but drag can be considered easily by MCOL. However, the difference between S-ALE and MCOL in this analysis is thought to have little effect on the sway velocity (as discussed in detail later).

Next, when using the CAM method, a decrease in the sway velocity can be observed as the equivalent added mass coefficient increases. This is a natural result of the increase in the displacement mass as the equivalent added mass coefficient becomes larger. The CAM results calculated with the equivalent added mass coefficient of 0.4 are in agreement with the MCOL results and S-ALE results until around 3 seconds. Although Motora *et al*. [5)] reported that the hydrodynamic effects can be evaluated by using an equivalent added mass coefficient of 0.4 when the duration of the collision is short, the trend is similar to their results. However, as the elapsed time increases, the velocities obtained by the MCOL and S-ALE methods decrease, while the results obtained by the CAM method converge on constant values for each of the equivalent added mass coefficients used in the analysis. This difference occurs because the effect of the wave damping force (memory effect) with temporal change is considered in MCOL and S-ALE, whereas in the CAM method, the damping effect is considered as a constant value which is included in the equivalent added mass coefficient. Fig. 5 presents results supporting this conclusion.

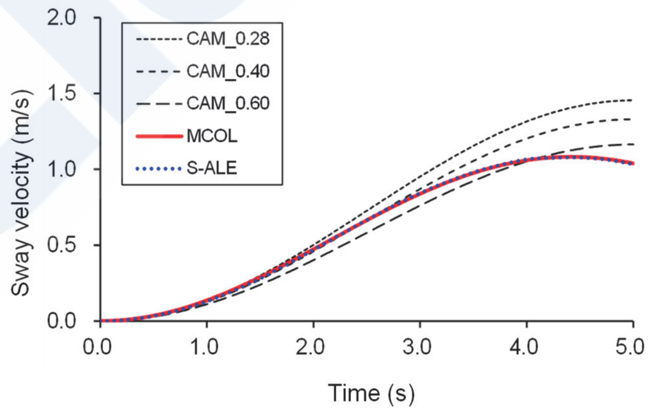


Fig. 4 Sway velocity of VLCC obtained by FEA with MCOL, S-ALE, and CAM. Equivalent added mass coefficients in CAM are 0.28 (infinite frequency), 0.40, and 0.60.

Fig. 5 shows the sway velocity in case all the hydrodynamic forces (added mass, wave damping force (memory effect), restoring force (stability), viscous force (drag)) are considered in the MCOL analysis, together with the sway velocity when each of the respective forces is not considered. The effects of restoring force (stability) and viscous force (drag) are extremely small. The effect of the wave damping force (memory effect) increases with elapsed time. Therefore, the sway velocity obtained by the CAM method, which uses an equivalent added mass coefficient, diverges from the results of MCOL and S-ALE with the passage of time. It is considered necessary to investigate the degree of effect that this difference has on the absorbed energy of the struck ship during a collision. The results of that investigation are presented in the following section.

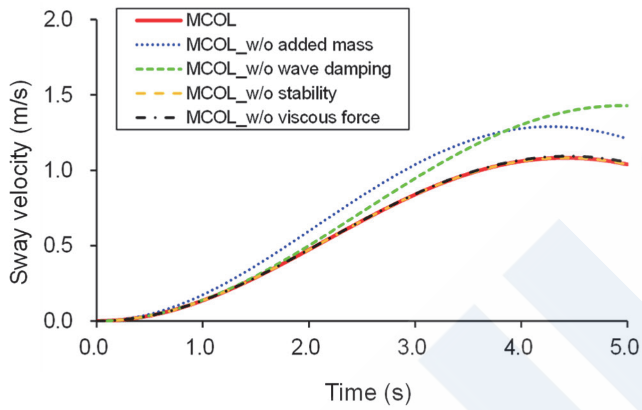


Fig. 5 Hydrodynamics effects on sway velocity of VLCC obtained by FEA with MCOL.

4.2 Sway Velocity, Contact Force and Absorbed Energy (Elastic-Plastic Body)

The ship central starboard side model (elastic-plastic body) was connected to the whole ship model (rigid body, 1 mass point, 6-DOF), and whole ship collision analyses were carried out using each of the hydrodynamic effects evaluation methods (MCOL, S-ALE, and CAM method). However, the hydrodynamic effects were considered only for the struck ship. Because the motion of the striking ship is limited to surge motion, coupling with the fluid is not considered. Since the focus of this research is to study the equivalent added mass coefficient of the struck ship, the hydrodynamic effects acting on the striking ship are an issue for future work.

Fig. 6 shows the condition at the final time of the simulation by S-ALE for the case where the surge velocity of the striking ship is 6 kt. Disturbance of the free (fluid) surface can be confirmed from the figure.

Fig. 7 shows the condition of damage (deformation and equivalent plastic strain distribution) of the elastic-plastic portion of the struck ship at the final time of the analysis with S-ALE when the surge velocity of the striking ship is 3 kt, 6 kt or 9 kt. The deformation of the struck ship increases as the surge velocity of the striking ship becomes larger. However, the reader should note that the bow section of the striking ship is treated as a rigid body, which means the deformation and damage that occur in the struck ship under the various collision scenarios are overestimated, in comparison with the case where the striking ship is modeled as an elastic-plastic body.

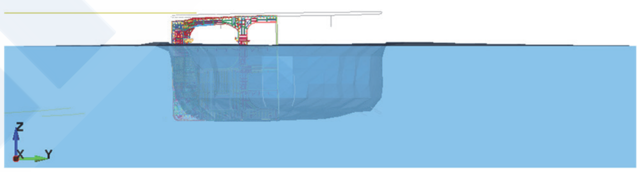
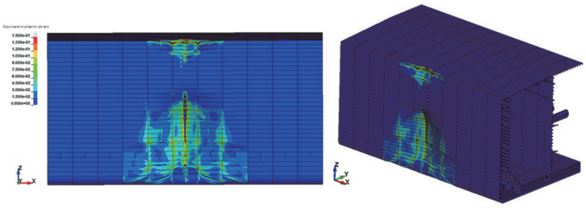
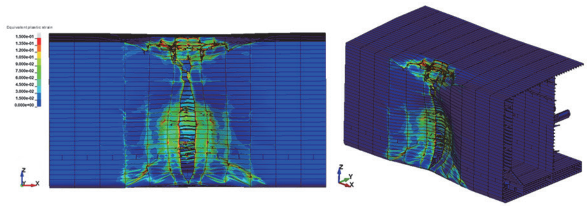


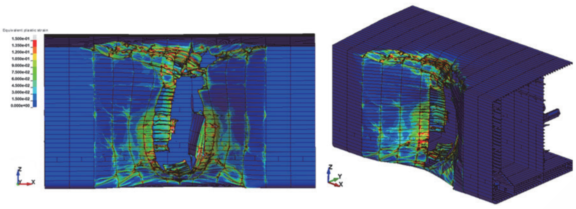
Fig. 6 Sway motion of the struck ship and disturbed fluid surface obtained by NLFEA with S-ALE at final time of simulation. Surge velocity of the striking ship is 6 kt.



(a) 3 kt



(b) 6 kt



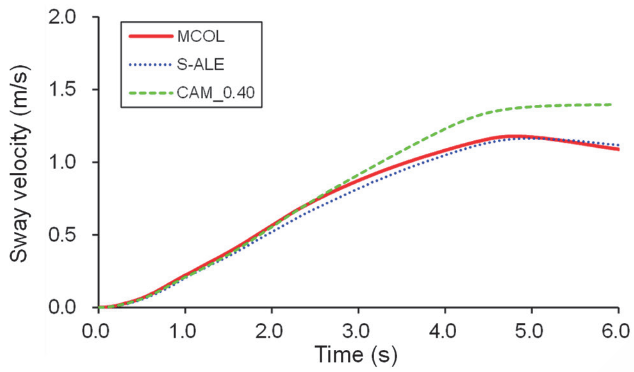
(c) 9 kt

Fig. 7 Structural damage (deformation and equivalent plastic strain) of the struck ship obtained by NLFEA with S-ALE at final time of simulation. Surge velocity of the striking ship: (a) 3 kt; (b) 6 kt; and (c) 9 kt.

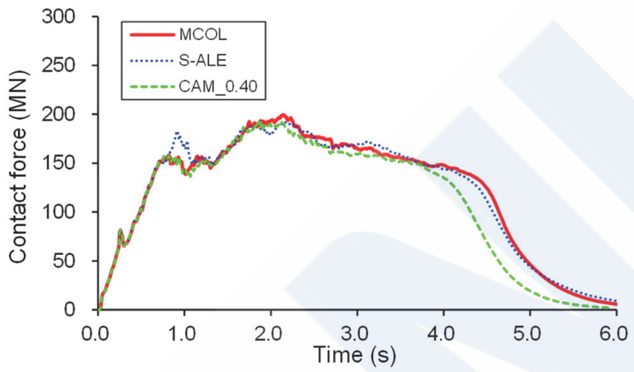
Fig. 8(a) shows a comparison of the sway velocity of the struck ship obtained by each of the hydrodynamic effects evaluation methods for the case where the surge velocity of the striking ship is 6 kt. Good agreement between the sway velocities obtained by MCOL and S-ALE can be confirmed from this figure. As in the case of the whole ship model without an elastic-plastic section described previously, almost identical results could be obtained by MCOL and S-ALE in the collision analysis including an elastic-plastic section. However, when the CAM method was used (equivalent added mass coefficient: 0.4), the sway velocity was similar to that given by MCOL and S-ALE until a collision duration of around 3 seconds, but became larger than the results by MCOL and S-ALE after that time. As discussed above, this divergence occurs because the CAM method treats the wave damping effect as a constant value.

Fig. 8(b) shows the time history of contact force. In this figure, the contact force history is almost the same by all the hydrodynamic effects evaluation methods until approximately 4 seconds, but the tendency of the S-ALE results differs from those of the other methods at around 1 second. This deviation occurs because only the S-ALE analysis considers the force of gravity. That is, the effect of gravity causes a slight upward displacement of the struck ship, and this changes the contact position with the striking ship. To support this conclusion, we conducted a separate S-ALE analysis in which the displacement of the struck ship in the height direction was constrained, and confirmed that the contact force history was the same as those obtained by the other hydrodynamic effects evaluation methods (MCOL and CAM method). Limited to the CAM method analysis, the contact force decreased after 4 seconds. This is because the sway velocity of the struck ship obtained by the CAM method exceeds the results of the MCOL and S-ALE after a certain time, as discussed previously.

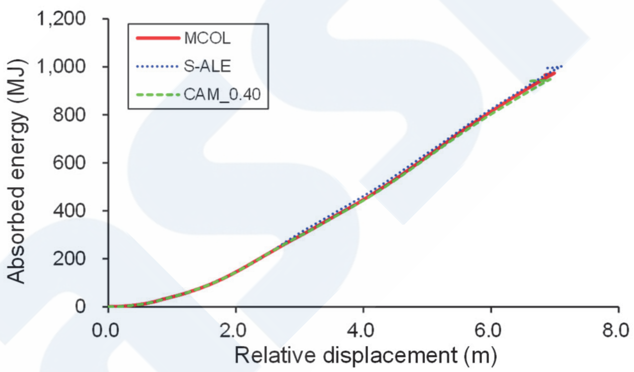
Fig. 8(c) shows absorbed energy, which was calculated by integrating the obtained contact force by the amount of penetration into the struck ship (in this research, this is treated as the relative displacement of the two vessels). Indexed to 1.00 by the CAM method (equivalent added mass coefficient: 0.4), the absorbed energy at the end of the collision (defined as the time when the velocities of the striking ship and struck ship become equal), was 1.02 by MCOL and 1.05 by S-ALE. Satisfactory agreement was obtained between the MCOL and S-ALE results, as the difference between the two was approximately 3%. On the other hand, when the surge velocity of the striking ship is 6 kt, these results showed that the CAM method (equivalent added mass coefficient: 0.4) estimates collision resistance performance slightly to the unsafe side.



(a) Sway velocity



(b) Contact force



(c) Absorbed energy

Fig. 8 Sway velocity, contact force, and absorbed energy obtained by NLFEA with MCOL, S-ALE and CAM (Equivalent added mass coefficient is 0.4). Surge velocity of the striking ship is 6 kt.

Finally, the CPU time (8CPU, MPP) required for collision analyses by each of the hydrodynamic effects evaluation methods discussed above was approximately 110 hours for the CAM method and MCOL, and approximately 120 hours for S-ALE. Since there is almost no difference between the CAM method and MCOL, it can be said that fluid-structure interaction analyses can be performed by MCOL without incurring a higher analysis cost. Moreover, although the longer analysis time required with S-ALE is considered a demerit, since the increase is limited to about 10 hours in comparison with the other methods, it was found that S-ALE can be used without problems under the analysis conditions of this study.

4.3 Calculation of Equivalent Added Mass Coefficient Using Analytical Solution

In order to evaluate the equivalent added mass coefficient from the absorbed energy obtained in the collision analyses by MCOL and S-ALE, the law of conservation of momentum and kinetic energy loss $\triangle E_k$ are considered. Assuming that the striking ship collides with the struck ship at right angles at the center of gravity position of the struck ship, the law of conservation of momentum is expressed by the following equation.

$$m_1(1+A_1)v_1 = [m_1(1+A_1) + m_2(1+A_2)]v_c \tag{3}$$

where, m_1 and m_2 are the displacement mass of the striking ship and the struck ship, A_1 and A_2 are the equivalent added mass coefficient of the striking ship and the struck ship, v_1 is the surge velocity of the striking ship, and v_c is the common velocity of the striking ship and the struck ship at the end of the collision. The kinetic energy loss $\triangle E_k$ at the end of the collision is expressed by the Eq. (4).

$$\Delta E_k = \frac{1}{2} m_1 (1 + A_1) v_1^2 - \frac{1}{2} [m_1 (1 + A_1) + m_2 (1 + A_2)] v_c^2 \tag{4}$$

The following equation can be derived by transforming Eq. (3) for the common velocity v_c and substituting the result into Eq. (4).

$$\Delta E_k = \frac{1}{2} \frac{m_1 (1 + A_1) m_2 (1 + A_2)}{m_1 (1 + A_1) + m_2 (1 + A_2)} v_1^2 \tag{5}$$

Eq. (5) was derived according to Minorsky [4]. Because the striking ship and struck ship in this study are the same type of ship, the displacement mass $m_1 = m_2$, and because the equivalent added mass coefficient of the striking ship is not considered, $A_1 = 0$. When these values are substituted into Eq. (5), Eq. (6) is obtained.

$$\Delta E_k = \frac{1}{2} \left(\frac{1 + A_2}{2 + A_2} \right) m_1 v_1^2 \tag{6}$$

As a result, the kinetic energy loss $\triangle E_k$ is expressed by the initial kinetic energy of the striking ship, $m_1 v_1^2 / 2$ and the equivalent added mass coefficient A_2 of the struck ship.

First, analytical accuracy was verified by comparing the calculated $\triangle E_k$ in Eq. (6) and the kinetic energy loss obtained by NLFEA using the CAM method (equivalent added mass coefficient: 0.4). Here, because the kinetic energy loss comprises the absorbed energy of the contact (frictional) energy and the internal energy of the struck ship at the end of the collision, the absorbed energy at the end of the collision by the CAM method (maximum value in Fig. 8(c)) and the value calculated by Eq. (6) were compared. In case the surge velocity of the striking ship is 6 kt, the values of absorbed energy obtained by the CAM method and the value of $\triangle E_k$ calculated by Eq. (6) were 948 MJ and 950 MJ, respectively, showing good agreement with an error of only 0.2%. As a result, the collision analysis results are valid. In the following, the value obtained by Eq. (6) will be treated as equal to the value obtained by the NLFEA using the CAM method. The NLFEA using the CAM method was carried out only for the case where the surge velocity of the striking ship is 6 kt. Table 5 shows the absorbed energies obtained by NLFEA using MCOL and S-ALE when the surge velocities of the striking ship are changed. The absorbed energies were nondimensionalized by division by the value calculated by Eq. (6) (equivalent added mass coefficient: 0.4). First, comparing the results by MCOL and S-ALE, the difference was on the order of 3%, even when the surge velocity of the striking ship was changed, confirming that almost the same results can be obtained by the two methods. It can be confirmed that the results calculated by Eq. (6) (equivalent added mass coefficient: 0.4) showed that this method estimates collision resistance performance approximately up to 8% to the unsafe side. It may be not appropriate to treat the equivalent added mass coefficient as a uniform value of 0.4 regardless of changes in the surge velocity, *etc*. of the striking ship.

Fig. 9 shows the absorbed energy obtained by MCOL and S-ALE for the initial kinetic energy of the striking ship, $m_1 v_1^2 / 2$. This figure indicates that the initial kinetic energy of the striking ship and the absorbed energy of the struck ship exist in a proportional relationship. This can also be confirmed from Eq. (6). In addition, by taking the slopes obtained from the approximate lines of the results of MCOL and S-ALE, and assuming they are equal to the equivalent added mass coefficient term on the right side of Eq. (6), i.e., $(1 + A_2) / (2 + A_2)$, it is possible to find the equivalent added mass coefficient calculated backward from the MCOL and S-ALE results. As a result, the equivalent added mass coefficient calculated backward from the MCOL results was 0.57, while that for S-ALE was 0.68, confirming that the values by these methods are significantly larger than the equivalent added mass coefficient of 0.4 which is used conventionally. This is consistent with the report by Motora *et al.*, as described in the Introduction. Here, there is a difference of approximately 20% between the equivalent added mass coefficients of 0.57 and 0.68 obtained by MCOL and S-ALE, respectively, but because the difference in the results for absorbed energy by these two methods was limited to about 3%, the effect of changes in the equivalent added mass coefficient on changes in absorbed energy is slight. Accordingly, when evaluating the absorbed energy of a target ship until the end of a collision, it is thought that collision resistance performance can be evaluated rationally and conservatively by setting the equivalent added mass coefficient at, for example, 0.7.

Table 5 Energy of the struck ship obtained by NLFEA with MCOL and S-ALE.

Surge velocity of striking ship (kt)	Energy* (MCOL/Eq. (6))	Energy* (S-ALE/Eq. (6))
3.0	0.99	1.04
6.0	1.02	1.05
9.0	1.05	1.08

*Note: Energy represents the value of absorbed energy obtained by NLFEA with MCOL or S-ALE divided by Eq. (6) with equivalent added mass coefficient 0.4.

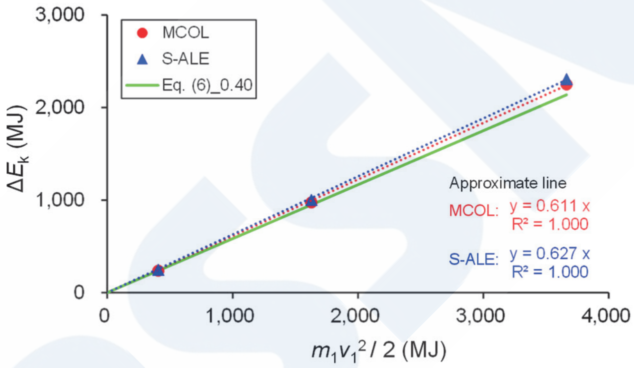


Fig. 9 ΔE_k obtained by NLFEA with MCOL and S-ALE.

5. CONCLUSION

A fluid-structure interaction analysis by MCOL and S-ALE was carried out for a ship-ship collision of two fully-loaded double-hulled VLCC using the commercial NLFEA program LS-DYNA in order to study the equivalent added mass coefficient for the sway motion of the struck ship. By deriving an appropriate equivalent added mass coefficient for the struck ship, a simpler and more rational evaluation of absorbed energy is possible. The knowledge obtained in this study is summarized below.

(1) It is possible to obtain substantially identical results in a sway velocity evaluation of a struck ship by MCOL and S-ALE, which can be used in LS-DYNA.

(2) If the absorbed energy of the struck ship at the end of the collision is evaluated using the conventional equivalent added mass coefficient of 0.4, an absorbed energy value smaller than those obtained by MCOL or S-ALE may be estimated, depending on the surge velocity of the striking ship, suggesting the possibility that the collision resistance performance of the ship may be estimated on the unsafe side.

(3) Since the effect of changes in the equivalent added mass coefficient on changes in absorbed energy is slight, it is appropriate, for a rational and conservative evaluation of collision resistance performance, to set an equivalent added mass coefficient on the order of 0.7 when evaluating the sway velocity of the struck ship.

Because this study only considered a double-hulled VLCC as the struck ship, collision analyses of different ship types, *etc.* may be mentioned as an issue for future work.

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