Experimental and Numerical Investigation of a Model-Scale Ship and Ice Floe (Second report)

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ABSTRACT

In earlier studies, the authors conducted small-scale model experiments and numerical analyses to assess the risk of situations in which a ship collides with a piece of ice. Analysis of velocity immediately before a collision is possible. Results show good agreement with the model tests. However, because of a problem in the analysis of the wave that the model ship induces, a difference was found in the detailed behavior of the ice piece before the collision. Furthermore, the velocity immediately before the collision was not measured with sufficient accuracy by the model test.

For this study, we improved the experimental apparatus so that we can measure the ice motion accurately up to the point immediately before the collision. A newly installed digital high-speed camera enables accurate observation of the ice motion. We also investigated a method to restrict the ice motion (degrees of freedom). Results show that the guide near the water surface affects the ice motion. We also improve numerical simulation methods to reduce the effects of wave propagation and reflection because these are unimportant in an actual ocean. Consequently, the ice motion in numerical analyses is quantitatively equivalent to that of the experiment.

INTRODUCTION

In recent years, commercial use of the Northern Sea Route and energy-resource development in the Arctic region have attracted attention. Because of decreasing ice in the Arctic Ocean area related to global warming, the Northern Sea Route has become increasingly available. Use of that route for commercial navigation is expected to increase (Otsuka, Izumiyama and Furuichi, 2013). However, independently floating ice are increasing along the Northern Sea Route, such as multi-year ice floes that have drifted from near the North Pole and icebergs that have broken off from glaciers. Consequently, the risks of ship collision with ice floes are increasing. To assess the safety and cost-performance of the Northern Sea Route and to evaluate its risk, it is desirable to analyze a situation in which a ship collides with floating ice, as described above.

Gagnon et al. (2008) opened study in this field by conducting actual ship experiments with a model test of collisions with floating ice, and by conducting numerical analyses. A few reports describe similar research efforts. The authors regard the phenomenon of collision between a ship and an ice piece as not investigated sufficiently. Especially, the effects of the flow field induced by the ship motion and the resulting ice motion have not been investigated well. It is expected that floating ice moves with momentum in a direction independently from that of a ship from the flow induced by ship motion. Although this momentum is slight in comparison to the ship momentum, considering the time scale of collision phenomena, some question remains about the validity of an analysis that ignores the ice piece momentum immediately before the collision.

Therefore, earlier studies of our group investigated the phenomena described above using model-scale experiments and numerical simulations. We developed an environment to conduct a small-scale collision experiment. Then we conducted collision experiments of a model ship and a synthetic ice piece. These experiments were conducted to evaluate and verify the numerical analysis. We also conducted numerical simulations up to the point immediately before the ship and the ice piece collide. Results of preliminary experiments and simulations were reported by Aso et al. (2013), Ishibashi et al. (2013), Shigihara et al. (2014), and Ishibashi et al. (2014).

In earlier studies, the measurement accuracy of the collision timing of a ship and ice was insufficient in experiments. In addition, in numerical simulations, ice was beginning to run before the collision because of the effects of waves that occur when the ship begins to run: the waves reflect from surrounding walls. Because these do not occur in an actual ocean, these waves are inappropriate.

For this study, we improved the experimental apparatus to measure the ice motion accurately up to the point immediately before the collision. We also investigated a method of restricting the ice motion. We also improved the numerical simulation method to reduce the effects of wave propagation and reflection because these are unimportant in an actual ocean. Consequently, the ice motion in the numerical analysis is the same as that of the experiment.

METHODS AND MATERIALS

Experiments

Most of the experimental apparatus is the same as that reported earlier (Ishibashi et al., 2014). Therefore, only an outline of the experimental apparatus and differences from the earlier devices are explained here.

Figure 1 portrays an outline of the experiments. Figure 2 depicts the experimental basin and its carriage. For this study, we used a small wave-making and towing tank at the Marine Ecosystem Engineering Laboratory, Institute of Industrial Science, The University of Tokyo. It has 6500 mm overall length, 1000 mm width, and 500 mm depth. Figure 3 portrays an overview of the measurement system.

The model ship (Figure 4) and the synthetic ice we used for the experiments described in this paper are the same as those used in the previous report. The overall length, breadth, height, and draft of the model ship are, respectively, 300 mm, 90 mm, 155 mm, and 90 mm. The synthetic ice size is 150 mm $\times$150 mm $\times$60 mm. Its density is 902 kg/m^3.

To simplify comparison with numerical simulation results, we developed guides of three different types for restricting the direction of motion (degrees of freedom) of the synthetic ice, as depicted in Figure 5. Here we call experiments with these guides Cases A, B, and C. In Cases A and B, a pair of cylindrical bars sandwich the ice near the top (Case A) or near the bottom (Case B). In Case C, a pair of thin, tightly tensioned strings sandwich the ice near the bottom. These guides inhibit sway motion, roll, and yaw rotation. Therefore, the ice can move in a surging and heaving motion with pitching rotation.

From the model test, the velocity and load are measured at the time of the collision of the model ship and synthetic ice. The ice motion is recorded with a newly introduced digital high-speed camera (Lumix DMC-FZ200; Panasonic Inc.). This camera is placed on the side of the basin. The video data are converted into a set of still images by 240 fps. Then the moving distance of synthetic ice is measured from them.

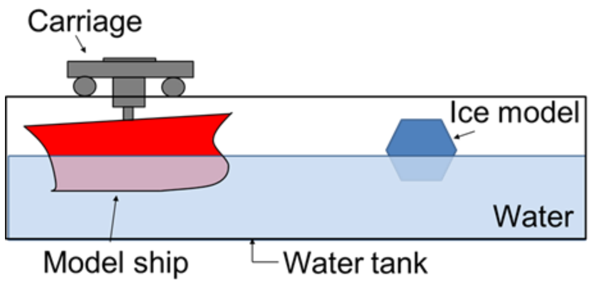


Figure 1. Outline of experimental apparatus.

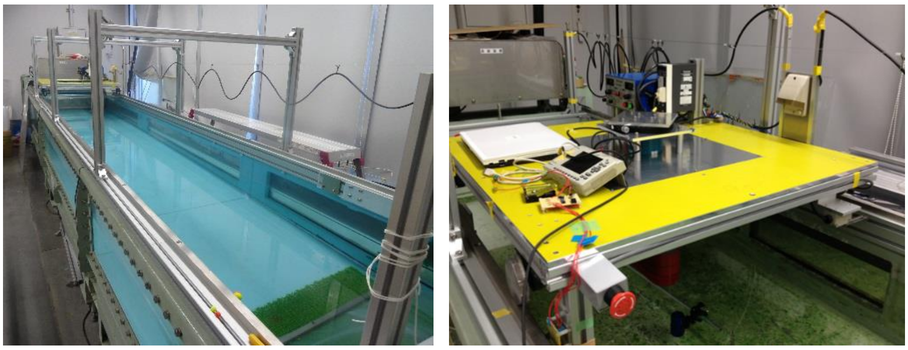


Figure 2. Photograph of the experimental basin and a carriage on it.

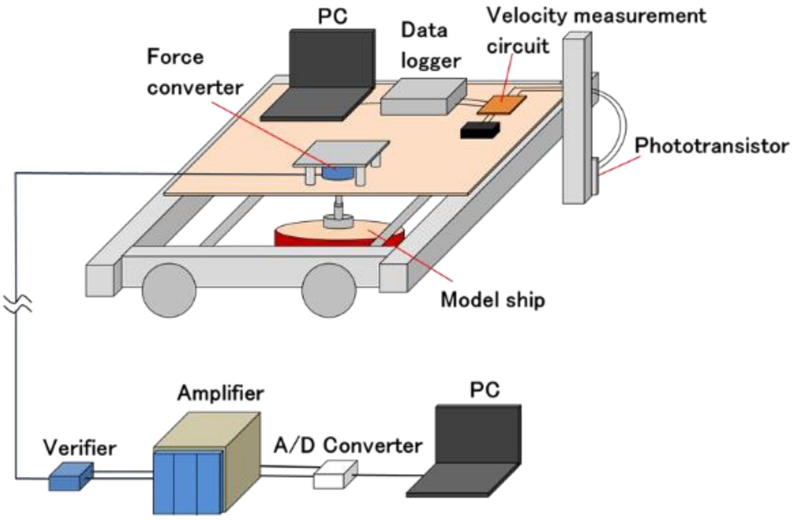


Figure 3. Overview of measurement system.

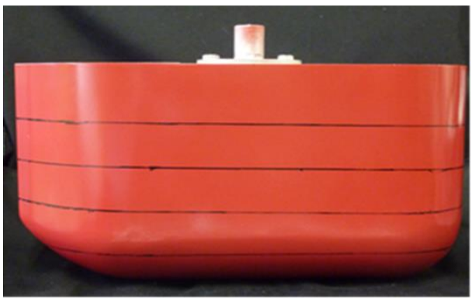
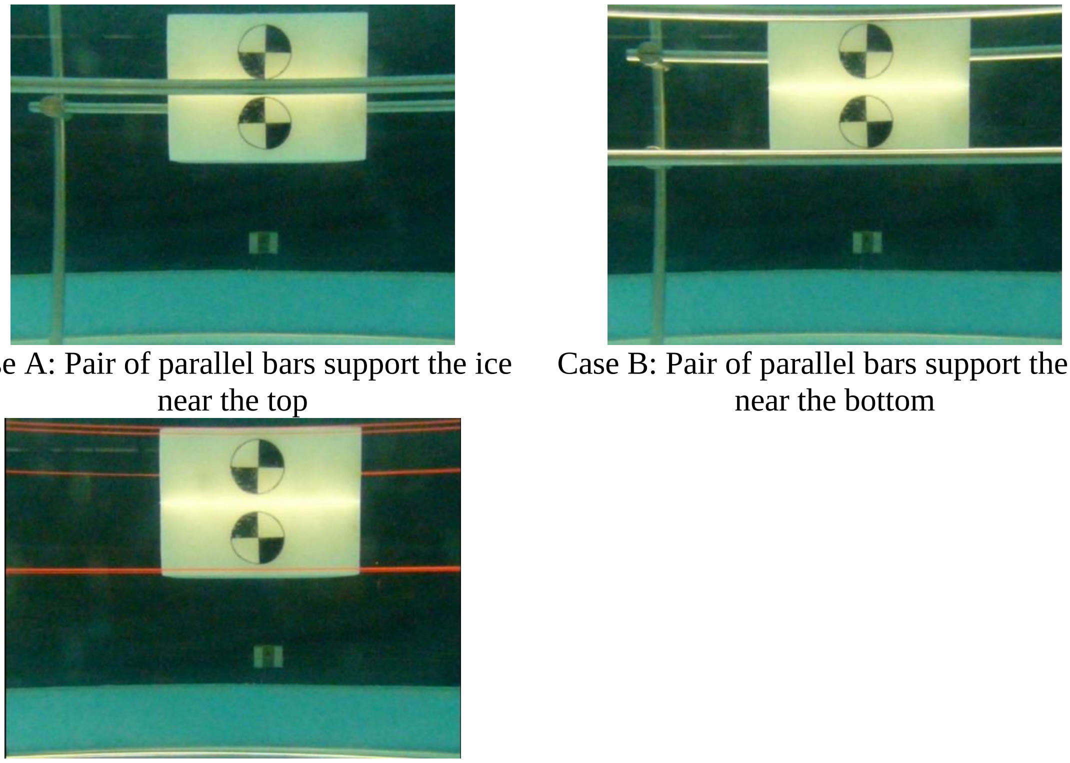


Figure 4. Photograph of the model ship (starboard side view).



Case A: Pair of parallel bars support the ice near the top

Case B: Pair of parallel bars support the ice near the bottom

Case C: Pair parallel strings support the ice near the bottom

Figure 5. Photographs of the synthetic ice with apparatus to restrict the ice motion (side view from underwater)

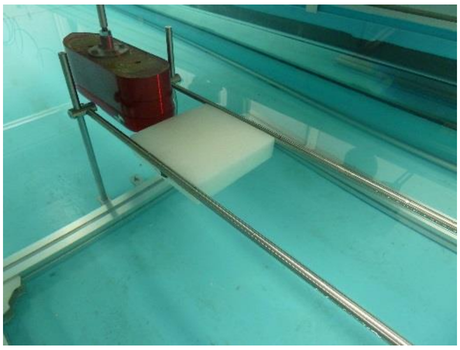


Figure 6. Photograph of the guide with the model ship and synthetic ice, Case A

Numerical Simulation

Because the numerical-analysis method is explained in the previous report (Ishibashi et al., 2014) as well as the experiment method, only the main analysis conditions and the difference from the previous report are explained here.

The analysis explained here reproduces the water-tank experiment described in the preceding section. For this simulation, we used commercial computational fluid dynamics simulation software (STAR-CCM+ v8.0.4; CD-adapco). STAR-CCM+ is provided with the overset method, which can represent moving bodies, and with the VOF method to represent free-surface flow. In addition, a Dynamic Fluid Body Interaction (DFBI) function is introduced, with which one can conduct analyses including those of six degree-of-freedom motion of a floating object. Our simulation uses all the functions explained above.

The analysis conditions used for this study are presented in Table 1 and Figure 7. For the present analysis, the analysis space size is 4500 mm × 1000 mm × 500 mm. The simulation domain length is less than that of the experiment because of the restriction of numerical simulation resources. Reflection of the wave on the edge of the simulation domain is damped numerically. Guides are not reproduced in the simulation.

The ice piece size is the same as that of the experiment: 150 mm × 150 mm × 60 mm.

In the previous study, the ship (carriage) velocity was always 0.5 m/s during the simulation. As described herein, the initial velocity of the ship is zero. The ship is first accelerated to a certain velocity (0.5 m/s). Then the speed is maintained, as shown in Figure 7.

Although we would like to obtain the flow field of the moment of a collision, it is difficult to analyze the flow field of the moment of a collision using this analytical method. Therefore, we simulate the phenomenon until the calculation stopped.

Table 1. Simulation conditions

Size of simulation space	4500 × 1000 × 500 mm
Minimum mesh size	5 mm
Number of meshes	5,642,156
Water density	1000 kg/m^3
Water viscosity	8.8871×10^{-4} Pa·s
Air density	1.18415 kg/m^3
Air viscosity	1.85508×10^{-5} Pa·s
Ice density	900 kg/m^3
Time step (Δt)	0.001 s

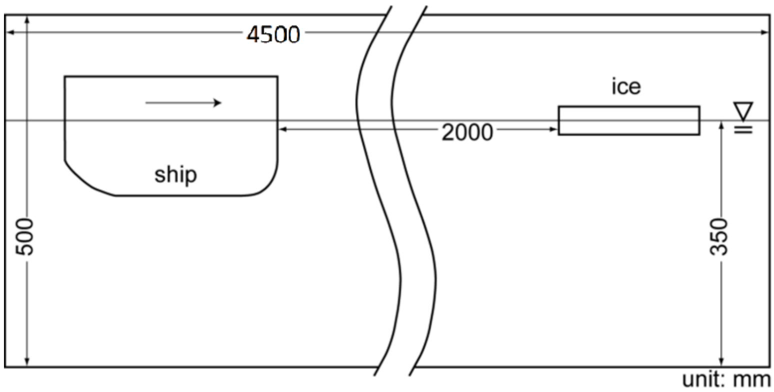


Figure 7. Illustration of initial condition of simulation.

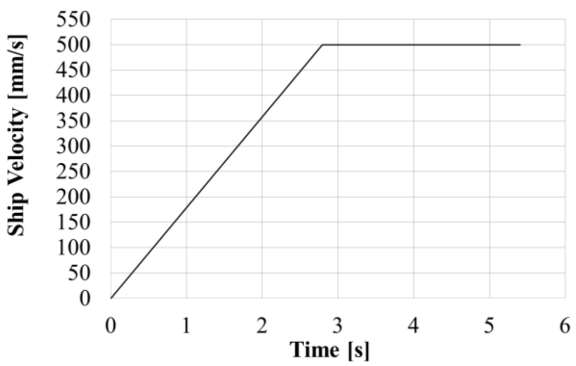


Figure 8. Time history of ship velocity in numerical simulation.

RESULTS

Experiments

Figure 8 depicts time histories of the measured load on the ship, ship speed, and ice displacement in Case A. Figures 9 and 10 respectively depict those in Cases B and C.

In these figures, the time when the load abruptly increases corresponds to the instant at which the ship and ice collided. Because a high-speed camera was used, the measurement accuracy of collision time improved.

These figures show that the ship velocity is about fixed, when the ship has collided with the ice. However, a ship velocity does not become a constant: it oscillates. This oscillation originates in the property of the speed controller of the carriage.

In Case A, the moving distance of the ice is smaller than in Cases B and C. Apparently that is true because, in Case A, the horizontal bars of the guide affects a wave because of the ship and ice motion.

Differences between Cases B and C are small.

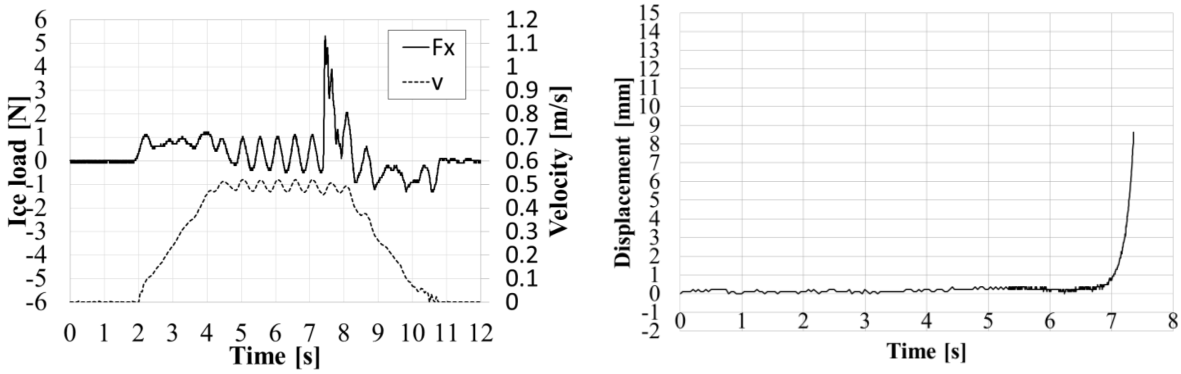


Figure 9. Time histories of load on the ship (left, solid line), ship speed (left, dashed line) and ice displacement (right). Case A.

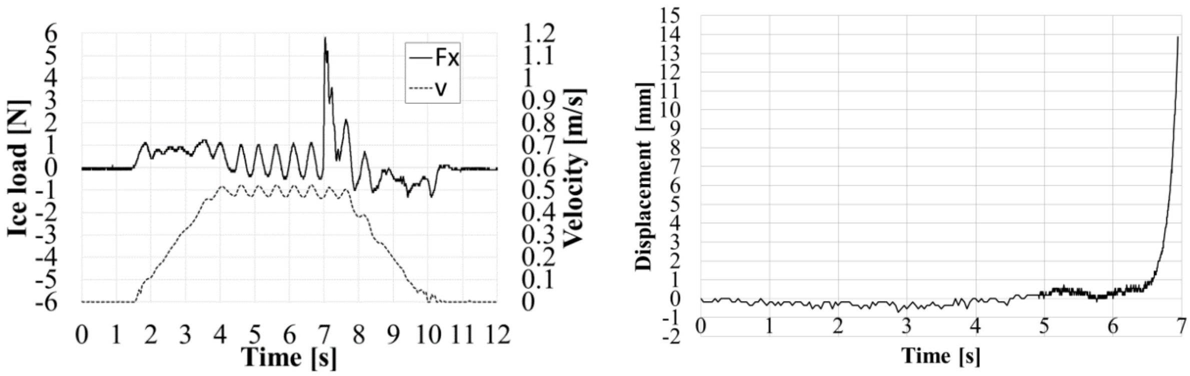


Figure 10. Time histories of load on the ship (left, solid line), ship speed (left, dashed line) and ice displacement (right). Case B.

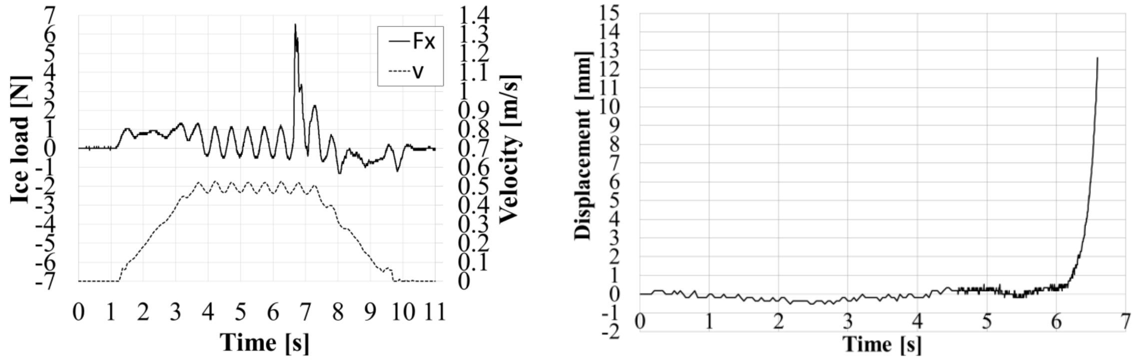


Figure 11. Time histories of load on the ship (left, solid line), ship speed (left, dashed line) and ice displacement (right). Case C

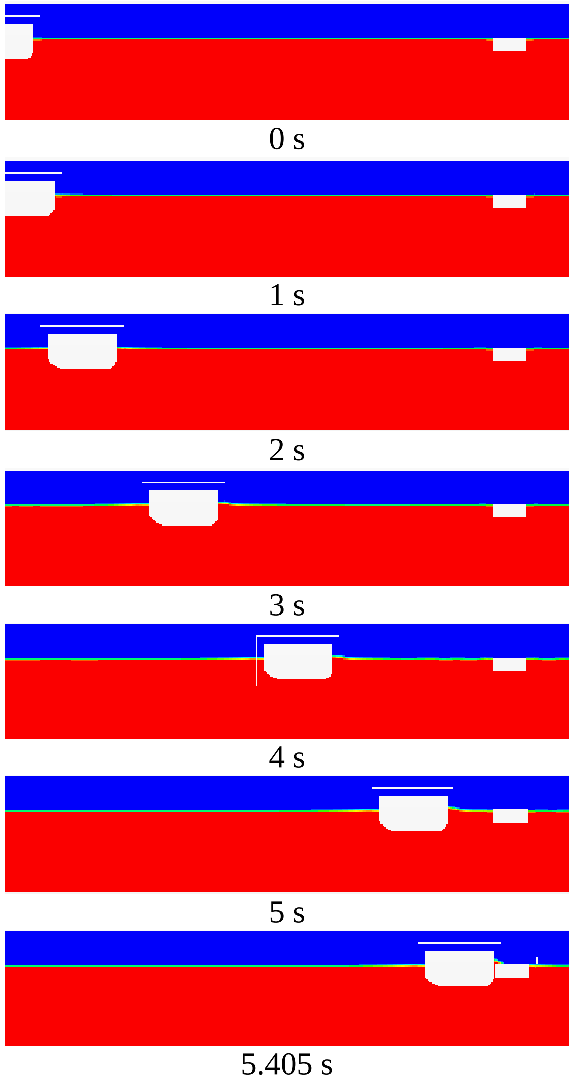


Figure 12. Motion of the ship, the ice piece, and the water surface at the central section of the simulation space.

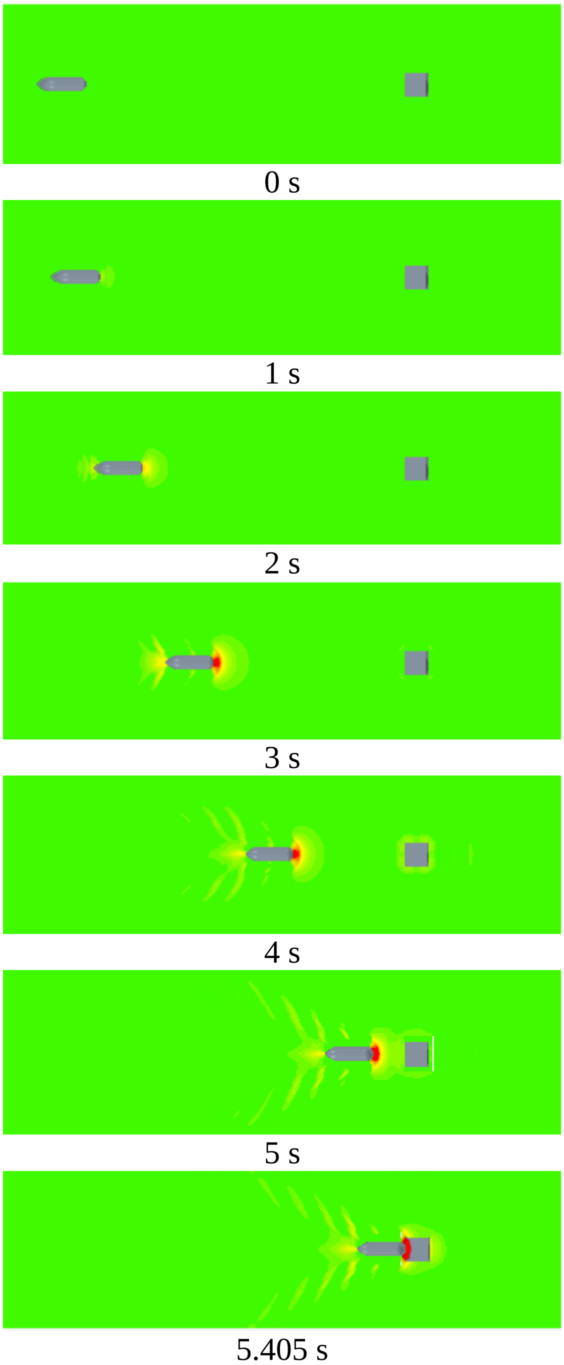


Figure 13. Motion of the ship, the ice piece, and water surface at the water surface section of the simulation space. Top view.

Numerical Simulation

Figure 12 depicts motions of the ship, the ice and water surface at the central section of the calculation domain in the numerical simulation. Figure 13 depicts those seen from the top, with color contours of the height of the water surface. This simulation ends immediately after 5.405 s.

Waves are induced by the ship movement. A previous report (Ishibashi et al., 2014) described that this wave caused the ice motion. In this simulation, however, no large movement of the ice was observed before the ship approached. In this study, the ship is accelerated from velocity 0 to a predetermined velocity. For this reason, the wave that arises by start of the ship is small. The effect is therefore decreased.

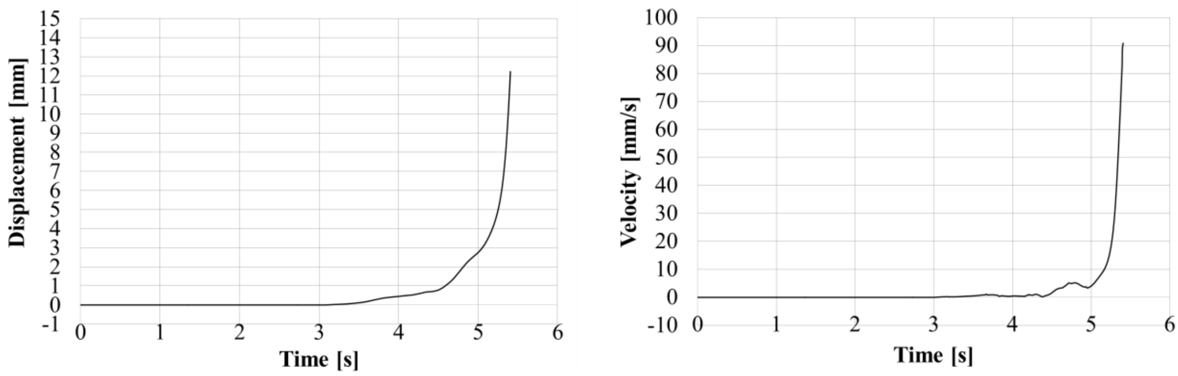


Figure 14. Time histories of ice displacement (left) and ice velocity (right) in the numerical simulation.

DISCUSSION

Because the difference between Cases B and C is small, the results of Case C can be compared with the numerical-analysis result.

Figure 15 depicts ship velocities and ice displacements in the model experiment (Case C) and the numerical simulation. The velocity is oscillating in the experiment. Improvement of the carriage speed controller is desired.

We divide the motion to the three parts: the first part (from the start until 4 s), the second part (between 4 s to about 5.2 s), and the last part (just before the collision). In the first part, the motions of the ice agree well. The motion is small. In the second part, the simulation result does not agree with the experimentally obtained result. In the last part, when the ship is about to collide with the ice, the motion agrees well again.

Apparently, the difference in propagated wave and reaction of the ice against the wave causes a difference in the motions. In the simulation, the guide is not reproduced, and the reflection of the wave is damped numerically.

We infer that it is not necessary to incorporate the effects of the guide and reflected wave into our simulation because there is neither a guide nor wall in the real ocean. As the motion of ice at the last part (just before the collision) agrees well, we consider that our simulation reproduces the ice motion successfully.

It must be described that it is also unimportant that the lines of ice displacements in Figure 15 are mutually close: the time of the collision depends on the motion during the first and the second part. It is important, however, that the lines be mutually parallel. If these lines are parallel, then the simulation produces a good estimate of the relative velocity of the ice against the ship immediately before the collision.

CONCLUSIONS

In this study, we improve experimental apparatuses so that we can accurately measure the ice motion up to the point immediately before the collision. A newly installed digital high-speed camera realizes accurate observation of the ice motion. We also investigated the method to restrict motion (degrees of freedom) of the ice, and found that the guide near the water surface affects the ice motion.

We also improve the numerical simulation method to reduce the effect of propagated wave and its reflection because these are unimportant in the real ocean. Consequently, the ice motion in the numerical analysis is quantitatively the same as that of the experiment.

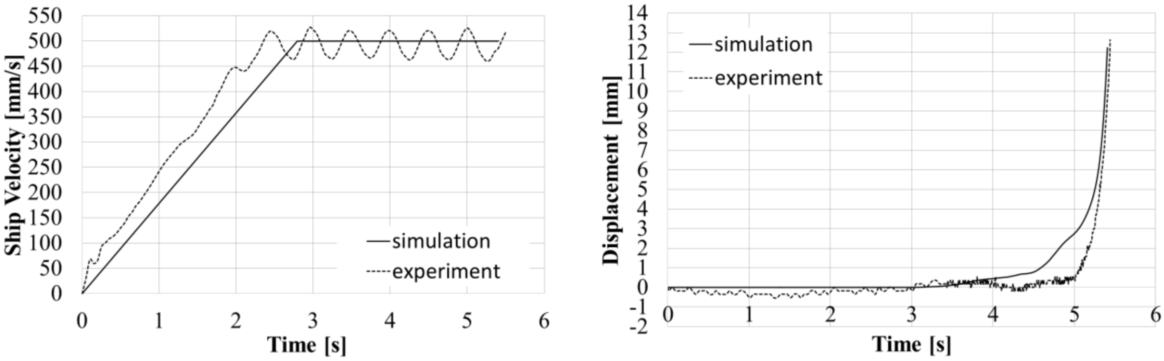


Figure 15. Comparison of ship velocity (left) and ice displacement (right) between the model experiment (Case C) and the numerical simulation.

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