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Distribution of Ice Load Acting on Model Hull due to Ship–Ice Interaction

Seong-Yeob Jeong[1], Kyungsik Choi[2], Jung-Seok Ha[1], Kuk-Jin Kang[1], and Eun-Jee Cheon[2]

[1]Korea Research Institute of Ships and Ocean Engineering, Daejeon, KOREA

[2] Departments of Ocean Engineering, Korea Maritime & Ocean University, Busan, KOREA

ABSTRACT
This paper details ice load distribution along the ship hull during ship–ice interaction. A model test was performed at the ice model basin in KRISO using the icebreaking model, *Araon*. This model was tested under the level ice condition in the free-running mode, wherein they were self-propelled without any constraint on their motion. Three tactile sensors were installed to measure the spatial distribution of ice load acting at different locations on a model ship, such as the bow and shoulder areas. Variation in the distribution of ice load acting on a model hull with ship speed is discussed.

INTRODUCTION
Knowledge about ice load distribution along the ship hull owing to ship–ice interaction can provide important background information for the development of design codes for ice-going vessels. Full-scale data obtained from field measurements is very useful, but field tests present several technical problems and are expensive. Therefore, a model-scale test in an ice tank could be an alternative for obtaining said information. Model-scale data provide valuable information about ice load distribution under normal and extreme operating conditions, and this data is difficult to obtain from full-scale field tests. To understand ice load distribution, many model tests have been performed in ice tanks. Izumiyama et al. (2001) conducted a series of resistance tests in ice, in which tactile sensors were employed to measure local ice loads. They compared the tactile sensor data to ship resistance in ice. In addition, Frederking (2004) studied ice pressure distribution using tactile-sensors.
The objective of the present study is to understand ship–ice interaction and ice load distribution along the ship hull. Free-running self-propulsion tests in ice were performed with three difference propeller revolution speeds. A discussion on the magnitude of ice load is presented.

MODEL TEST IN ICE TANK
Model tests were conducted in an ice tank at the Korea Research Institute of Ships and Ocean engineering (KRISO). The KRISO ice tank contains EG/AD-CD model ice; EG, AD, and CD stand for ethylene glycol, aliphatic detergent, and controlled density, respectively. The model ice is similar to that used by National Research Council-Ocean, Coastal, and River Engineering (NRC-OCRE, formerly NRC-IOT). In preparing the model ice, micro-bubbles were discharged uniformly from the bottom of the ice tank over the entire ice-grown area throughout the freezing process. This was done to ensure that the model ice density simulated the natural density range of Arctic Sea ice. The dimensions of the ice tank were as follows: 42 m (long) × 32 m (wide) × 2.5 m (deep). The size and shape of the ice tank were designed to enhance the maneuvering performance of ice-going vessels in ice and the model test

capabilities of offshore structures operating in the Arctic. In a typical ship resistance or propulsion test, the 32 m of ice width available in the KRISO tank allows for more than five or six parallel test channels within one ice sheet. Figure 1 shows the model ice prepared in KRISO's ice tank.

Figure 1 Generated EG/AD-CD model ice in KRISO ice tank

Calibration of tactile sensor

The tactile sensor should be calibrated to convert sensor output (raw sum) to ice load. However, tactile sensor calibration is not straightforward because tactile sensors do not output a constant value under a constant applied load. This phenomenon is related to sensor sensitivity, test environment conditions, etc. Thus far, various methods have been used to calibrate the output of tactile sensors. Izumiyama *et al*. (2001) calibrated a tactile sensor in terms of the relationship between the normal load on the hull and the resistance component. Lu *et al*. (2013) used the two-point method to calibrate a tactile sensor with different sensitivities. Sodhi *et al*. (2001) analyzed the data obtained using a tactile sensor in a field indentation test in Hokkaido.

In this study, calibration is performed in a manner similar to that under the model test condition. Indentation tests are conducted for calibration before the model test. For calibration, we first apply a waterproof film cover to a tactile sensor. The sensor is then mounted on a plate connected to a one-axis dynamometer, and a load acting through the tactile sensor is applied. Herein, a wooden plate is used to simulate the model ship in order to maintain an environmental condition similar to that in the model test. The data measurement frequency of the tactile sensor and the dynamometer is 100 Hz. By following the abovementioned procedure, the relationship between applied load and sensor output, and calibration factor are determined. The tactile sensor calibration method is shown schematically in Figure 2, and the ice load measured using the one-axis dynamometer and the calibrated ice load from the tactile sensor in the indentation test are shown in Figure 3. In particular, Figure 3 shows the slight variations between the values of ice load obtained using the tactile sensor and the one-axis dynamometer, as observed in the calibration test. However, broadly, the ice load measured with the one-axis dynamometer agrees well with the calibrated ice load obtained using the tactile sensor.

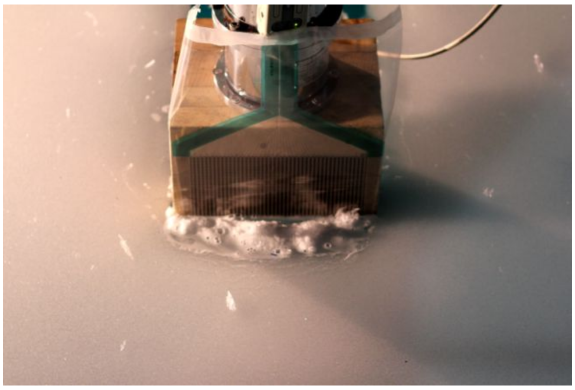

Figure 2 Tactile sensor calibration test

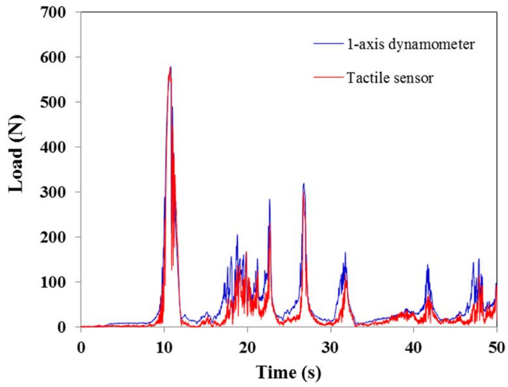

Figure 3 Calibrated ice load results of tactile sensor in indentation test

Description of model test

The model test for the icebreaker model *Araon* was performed. Icebreaker *Araon* is designed to navigate to the Arctic and other ice-covered areas where first-year ice is encountered. The model was manufactured to the scale of λ = 18.667 and has both azimuth units. The specific dimensions of the icebreaker model ship and the ice condition of the model test are summarized in Tables 1 and 2, respectively.

Table 1 Principal particulars of the icebreaker *Araon*

Scale (λ = 18.667)	**Model**
Length between perpendiculars (m)	5.01
Maximum beam (m)	1.02
Design waterline (m)	0.36
Stem angle (°)	35.0
Waterline entrance angle (°)	34.0
Displacement (kg)	1142

Table 2 Model test conditions

Ice thickness (mm)	**Ice strength (kPa)**	**RPS (1/s)**	**Model ship speed (m/s)**
52.8	21.9	8.0	0.206
54.6	23.0	11.0	0.354
55.4	36.5	12.0	0.704

Three tactile sensors were installed on the bow and shoulder areas to measure the ice load during icebreaking. Self-propulsion tests were performed in level ice at three different propeller revolution speeds. The developed thrust, torque, and model ship speed were recorded when the model ship achieved a steady speed in ice. This period is called the sampling section. The model test involved motion along a straight line and was performed using the design draft of the model ship. As mentioned before, a system of tactile sensors, namely, I-SCAN system, was used to measure the ice load acting on the model hull. This system was composed of tactile sensors, a PC, and handles. In particular, the handles read data from the tactile sensor and transmitted it to the PC. Ice load acts close to the hull waterline. Therefore, three tactile sensors were attached close to the waterline regions. Figure 4 shows the tactile sensor installation locations.

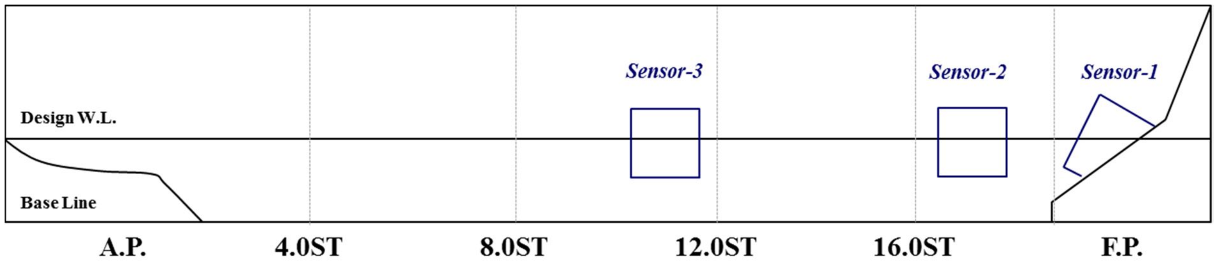

Figure 4 Location of tactile sensors in straight motion test

ANALYSIS OF ICE LOAD DATA

The model test results should provide valuable information about the magnitude of ice load acting on a ship hull. In this section, the magnitude of ice load acting on the bow and shoulder regions, as obtained from the model test, are discussed.

Ice load distribution

Data measured by a tactile sensor can be analyzed as a value corresponding to the total load within the sensing area. The sensing spots in tactile sensor used herein are arranged in a 44 × 44 grid. The inter-row and -column spacing was 0.54 cm, and the sensel area was about 0.29 cm^2. Figure 5 shows the measured ice load history during icebreaking. Herein, the icebreaking cycle occurs within a few seconds, and a large ice load was recorded before failure of the ice sheet. The icebreaking cycle takes place within approximately 0.1 to 0.4 s at the model scale. At full scale, the icebreaking cycle takes about 0.4 to 1.7 s. In the data sampling section, the maximum and average ice loads were obtained, and the results are summarized in Tables 3–5.

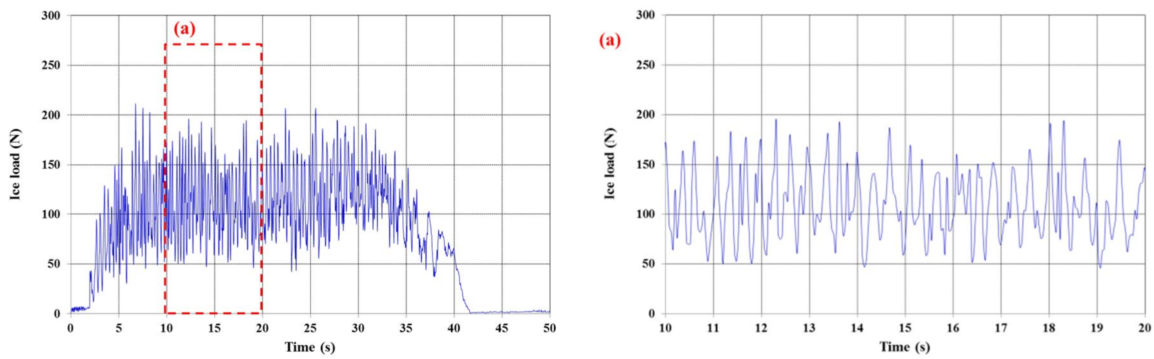

Figure 5 Measured ice load in model test. (a) denotes the sample of icebreaking cycle during icebreaking

In Tables 3 and 4, when the model ship speed increases, ice load along the normal direction increase as well, and this tendency can be observed in the forward shoulder area (*Sensor-2*) too. That is because when a model ship enters an ice sheet, crushing occurs at the stem and continues to increase in the contact area until bending failure of the ice sheet. In the mid-shoulder area (*Sensor-3*), there is no direct correlation between the model ship speed and magnitude of ice load, but the magnitude of ice load may be related to contact between the rotated broken ice pieces and the model hull. From the viewpoint of hull scantling, the maximum magnitude of ice load is more significant than the average ice load; thus, the measured maximum ice loads at each tactile sensor location were recorded and are shown in Figure 6.

Table 3 Calculated maximum and average ice loads in bow area (*Sensor-1*)

Model ship speed (m/s)	Maximum ice load (N)	Average ice load (N)
0.206	70.9	19.2
0.354	66.5	36.7
0.704	206.9	121.9

Table 4 Calculated maximum and average ice loads in shoulder area (*Sensor-2*)

Model ship speed (m/s)	Maximum ice load (N)	Average ice load (N)
0.206	37.2	7.3
0.354	69.6	10.1
0.704	89.7	21.2

Table 5 Calculated maximum and average ice loads in mid shoulder area (*Sensor-3*)

Model ship speed (m/s)	Maximum ice load (N)	Average ice load (N)
0.206	22.0	3.3
0.354	16.1	4.7
0.704	21.8	8.8

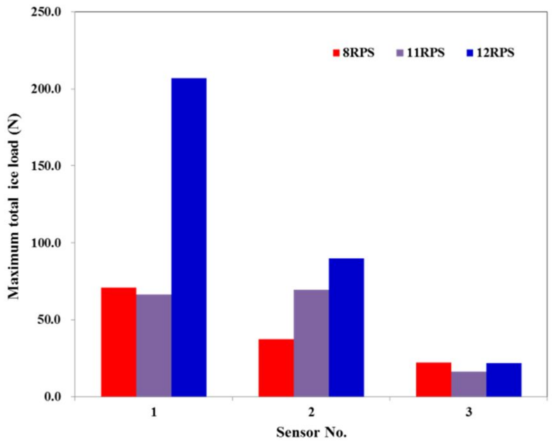

Figure 6 Maximum ice loads results for each sensor location

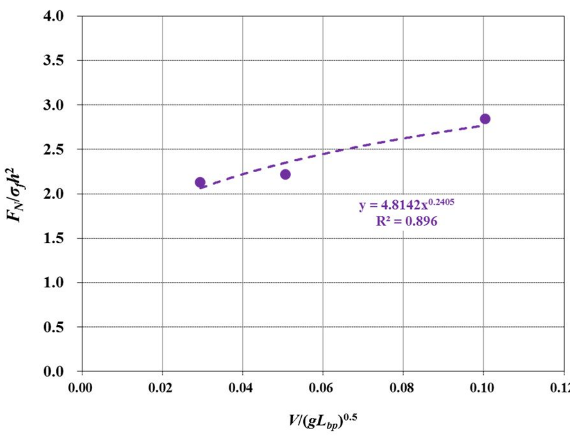

Figure 7 Non-dimensional relationships between normal ice load and model ship speed

In particular, there is some difference in ice thickness and strength in the model tests. Thus, two non-dimensional parameters were adopted. Non-dimensional normal ice load is obtained by dividing the flexural strength of the model ice by the square of ice thickness, and model ship speed is non-dimensionalized by using a length between perpendiculars, $L_{bp,}$ based on the Froude number. As shown in Figure 7, when the non-dimensional model ship speed increases, non-dimensional normal ice increases as well. This is because the normal contact area due to ship–ice interaction attributed to increased normal ice loads in high speed range. Although there is some scatter, the fitted curve shows a relatively good correlation between two non-dimensional parameters ($R^2 = 0.896$).

SUMMARY

To determine the magnitude of ice load acting along a ship hull during ship–ice interaction, a model test was performed in the ice model basin in KRISO with the icebreaking model ship *Araon*. This model was tested under the level ice condition in the free-running mode, in which they were self-propelled without constraints on their motion. Three tactile sensors were installed in different locations such as the bow and shoulder areas. The main findings of this study are as follows:

1) To calibrate the output value of a tactile sensor, indentation tests in a manner similar to that under the model test condition were conducted before the model test. Ice load measured using the one-axis dynamometer agreed fairly well with the calibrated ice load recorded using the tactile sensor.
2) In the model test, icebreaking occurred between 0.1 and 0.4 s at the model scale. At full scale, icebreaking occurred between 0.4 and 1.7 seconds, and a large ice load was recorded before failure of the ice sheet.
3) Generally, a large ice load acts in the bow area in the straight-motion test, and there is a direction correction in the speed range. The magnitude of ice load in the mid-shoulder area may be related to the contact relationship between rotated broken ice pieces and the model hull than icebreaking force components.

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