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Experimental research on resistance and motion attitude variation of ship–wave–ice interaction in marginal ice zones

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ABSTRACT

Wave–ice floe interactions increasingly threaten the safety of ice-going ships with the expansion of the marginal ice zone (MIZ). Therefore, studies must focus on the resistance of ice-going ships in the MIZ. Model testing is a feasible and practical method for conducting such research. In this study, the Harbin Engineering University's towing tank equipped with a wave generator was used to simulate the special environment of the MIZ by using paraffin as model ice. A ship model resistance test is conducted under the combined effects of waves and ice floes. The study results show that the motion of the ship model is more unstable in the MIZ than in ice floes. Furthermore, the degree of the ship–ice interaction increases under the wave–ice interaction. The test results show that the total ship resistance is not equal to the sum of the open-water resistance, wave-added resistance, and ice floe resistance because of the wave–ice floe–ship interaction. The increase in resistance resulting from the combination of these three components must be considered while designing an ice-going ship. Finally, we discussed the influence of the parameters associated with the wave length, wave height, and ice concentration on the added coupling resistance.

1. Introduction

The marginal ice zone (MIZ) is generally defined as a transition region from open water to pack ice with low-concentration, low-thickness, and diffuse sea ice floes of varying shapes and sizes [1]. Level ice is broken up by waves propagated from the open water, resulting in the formation of an area in which both ice floes and waves exist. Therefore, the main morphological feature of the MIZ is the wave–ice floe interaction. Studies in the east of Antarctica have shown that within a short distance (~60 km) from open water, ice floe pieces are very small and relatively uniform in size, with typical diameters of ~0.1 m. At a greater distance (~190 km), the ice floe diameter gradually increases from 0.5 to 8 m. At distances greater than 190 km, the ice flow diameter can increase to 100 m or more [2]. Many studies have investigated the size and distribution of ice floes. Toyota et al. analysed the size distribution and shape properties of relatively small sea ice floes in the Antarctic MIZ in late winter [3]. Williams et al. analysed wave–ice interactions in the MIZ through numerical and sensitivity studies; specifically, they analysed the properties of the wave field and sea ice properties such as concentration, thickness, and breaking strain [4]. Gupta studied sea ice roughness in the MIZ through physical roughness measurements [5].

Early studies of the MIZ mainly focused on the wave–ice interaction [6]. Few studies focused on ice-going ships in the MIZ. The MIZ is an important and unavoidable zone for ice-going ships sailing in the Antarctic and Arctic regions. A ship's resistance in the MIZ differs from that in ice floes without waves. Ships interact with both ice floes and waves. This complex interaction is called the

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ship–ice–wave coupling. Therefore, it is important to study the resistance of ships sailing in the presence of waves and ice floes. Ice-going ships have longer required icebreakers to clear the way to safely pass through Arctic routes [7]. Most studies on the ice-going ships' resistance have examined the ships' performance in level ice conditions or in a brash ice channel environment. However, data from the US National Snow and Ice Data Center indicates that the average monthly Arctic sea ice extent in October decreased by nearly 6% annually from 1978 to 2014. In other words, the extent of the MIZ is steadily increasing, and the extent of level ice is gradually decreasing. As a result, it is gradually becoming possible for commercial ice-strengthened ships to operate in the Arctic.

In the last few decades, many studies have focused on model tests of ships' resistance in ice without waves. In 1964, Corlett and Snaith conducted the first study on the resistance of ice-going ships by using paraffin as model ice to measure a small Baltic Sea icebreaker's resistance [8]. Enkvist (1972), Edwards et al. (1972), Johansson and Mäkinen (1973), and Poznak and Ionov (1981) estimated the resistance of ice-going ships in level ice by using empirical formulae and model tests [9]. Kitazawa and Ettema (1984) designed a simulated brash ice channel in a towing tank to investigate commercial ships' resistance [10]. Loset (1998) conducted two model test series of turret moored tankers in ice [11]. Daley (1998) analysed ship–ice interactions by using the discrete element method [12]. Spencer divided ice-going ships' resistance into four components: ice-breaking resistance, submersion resistance, ice-clearing resistance, and open-water resistance. Furthermore, he established an analysis method for ship model resistance testing in level ice used in ice tank testing in South Korea and elsewhere [13,14]. Aboulazm [15] summarised various formulae for estimating ships' resistance in ice floes under different ice conditions. He also used paraffin as model ice to measure ships' model resistance and then proposed a theoretical model for ship–ice floe interaction. Ice floe resistance is mostly considered a component of the total ship resistance in level ice or an ice-going ship's resistance in a brash ice channel. Kim et al. conducted a few model tests of ship resistance in level ice and crushed ice from 2006 to 2011 and studied the relationship between ship shape and resistance [16–19]. In 2010, Jeong et al. conducted a model test in the MOERI (Maritime and Ocean Engineering Research Institute) ice tank to study ice resistance [20]. In 2013, Kim et al. compared simulation results with model ice results of ship resistance [21]. Ehlers et al. conducted various model tests of icebreakers; they studied the ship resistance and ice-breaking patterns [22], properties of model ice [23,24], and influence of bow design on ice-breaking resistance [25].

Researchers, including Bennett and Squire [26], have continued to focus on the wave–sea ice interaction mechanism. However, few studies have focused on wave–ice–structure interactions. McGovern studied the relationship among waves, ice, and an isolated circular marine cylinder. However, little research has been conducted on ships' resistance under the combined action of waves and ice [27].

In this paper, paraffin was used as unbroken model ice to study ice-going ships' resistance under the combined wave–ice floe interaction. Tests were conducted in a towing tank equipped with a wave generation system. Model ice was distributed with different concentrations in the towing tank. Appropriate wave parameters were determined to act with the model ship and ice floes. The resistance in open water, ice floes without waves, and ice floes with waves was measured. Then, the resistance under different conditions was compared to analyse the ship–ice and ship–wave–ice interactions. The test model is the 76000 DWT (deadweight tonnage) ice-strengthened Panamax Bulker. Panamax Bulker has a different hull ship compared to container ships, warships, and other types of ships. The free surface waves are also different. Finally, the ice distribution and resistance are also different under the combined wave–ice floes interaction. Therefore, the findings of this study are generally dependent on the hull shape.

2. Experimental systems

2.1. Test model

In this study, the test model used is the 76000 DWT ice-strengthened Panamax Bulker. Table 1 lists the principal dimensions of the tested bulk carrier. Turbulence stimulators were installed at 5% length between perpendiculars (LPP) away from the forward perpendicular (FP) to minimise the scaling effect induced by the conflict between Froude and Reynolds scaling.

2.2. Scaling law

When ships navigate in the MIZ, three types of forces act on them: gravity, inertia, and friction. The Froude number (Fr) is a dimensionless number that is defined as the ratio of the flow inertia to the external field (in many applications, the latter is simply due to gravity). The Reynolds number (Re) is defined as the ratio of inertial forces to viscous forces within a fluid which is subjected to relative internal movement due to different fluid velocities. Model tests must be performed such that the model- and full-scale ships

Table 1
Principal dimensions of test model.

Principal hull data	Model-scale ship	Full-scale ship
Scale	45	1
L_{oa} [m]	5.00	225
L_{pp} [m]	4.82	217
B [m]	0.72	32.25
D [m]	0.45	20.10
T [m]	0.28	12.40