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Evaluation of selected state-of-the-art methods for ship transit simulation in various ice conditions based on full-scale measurement

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ABSTRACT

For the design and transit simulation of ice-going ships, a number of methods have been proposed for the prediction of ship resistance and transit speed in various ice conditions. In this paper, selected methods for ship performance in level ice, ridged ice and channel ice are evaluated based on full-scale measurement data of two ships. Uncertainties are identified and evaluated for a better understanding of the deviations in the results.

Ice thickness in full-scale data was measured using multiple methods to minimize the uncertainty. The thickness of level ice was measured by a stereo camera system. The ridge profile was identified through measurement with an electromagnetic device. Visual observation was conducted for the description of encountered ice conditions. For a better estimation of ship net thrust through propulsive data, the net thrust model is revised in this paper to take the effect of power and propeller pitch into consideration.

The results show that for transit simulation, the selected methods for level ice give acceptable prediction of ship speed with certain underestimation. For ridged ice, the method seems to underestimate the speed, especially when a ship needs to conduct ramming operation. Data acquisition is the most problematic for the investigation of channel ice. The uncertainties due to the modelling of sub-processes and ice properties lead to certain scatter in applying these methods for speed prediction. Possible improvements are given as the conclusion of this work.

1. Introduction

The navigation through the northern sea route has received increasing attention during recent years due to the decreasing Arctic sea ice extent (Beveridge et al., 2016; Stoddard et al., 2016). Prediction methods on ship performance in ice have been proposed to evaluate the attainable speed and endured resistance of vessels navigating in various ice environments. These methods are intended to be used for ship design, aiming at minimizing the ship resistance. Another use is transit simulation, aiming at evaluating the voyage time and fuel cost, which helps shipping companies to analyse the operability and profitability of a potential route. The importance of understanding the uncertainties in the models applied for these purposes has been recognized e.g. by Choi et al. (2015) and Bergström et al. (2017).

Semi-empirical formulae have been widely used for engineering ship design and regulatory design requirements. Formulae for level ice resistance calculation are usually developed through an analytical breakdown into several resistance components and then modelling each component by analytical, empirical or combined approaches (Enkvist, 1972; Lindqvist, 1989; Kämäräinen, 1993; Riska et al., 1997). Existing semi-empirical formulae for level ice resistance calculation are reviewed in detail by Kämäräinen (1993) as well as Erceg and Ehlers (2017). There are fewer formulae for ship resistance in ridged ice and channel ice compared to level ice. These are usually studied by exploiting similarities between mechanics of ice rubble or brash ice and soil mechanics (Mellor, 1980; Malmberg, 1983; Riska et al., 1997).

Several numerical methods have been presented in recent years for the prediction of ship performance in ice and ice loads on ship hull. Some of these are developed by combining the numerical approach with semi-empirical sub-models (Wang, 2001; Su et al., 2010). Minor modifications regarding the breaking process have been made to the model of Su et al. (2010) by other researchers (Tan et al., 2014; Su et al., 2014; Zhou et al., 2016). The other methods model the ice breaking processes either by analytical calculation (Lubbad and Løset, 2011) or by numerical tools, such as Finite Element Method (FEM) (Sawamura et al., 2008), Discrete Element Method (DEM) (Lau, 2006) and combined Computational Fluid Dynamics (CFD) and FEM (Valanto, 2001). Numerical methods for ships in ridged ice and channel ice are rare due to the complexity of these physical environments. The discrete element method is applied for ships going through ice ridges (Gong

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et al., 2017) and channels (Sorsimo et al., 2016), which is computationally very expensive. Finally, data-driven approaches have been proposed in recent years for the operability of ships in different ice environments (Montewka et al., 2015; Fu et al., 2016; Li et al., 2017), but these are still in the early stages of development.

Ice conditions measurement is the key to the accuracy of full-scale data. The traditional drill-a-hole method can give accurate information at a specific location but is not practicable for describing the ice conditions along the whole route, especially when it comes to ridges where the thickness variation is significant. Visual observation could be used to estimate ice thickness along the route. However, visual observation is featured with high uncertainty. Since ridge keel profile is invisible to observers, the geometry of the keel is usually estimated from the observed sail height, which is a rather rough estimation. These inaccuracies introduce uncertainties when these measurement data are deployed for validation. However, it is noticed that most resistance prediction methods were validated with ice data obtained via traditional drill-a-hole or visual observation methods (e.g. Kämäräinen, 1993; Su et al., 2010). In this paper, the state-of-the-art measuring equipment gives accurate data with high spatial and temporal resolution, thus providing robust evidence for evaluating model performance. In addition, the net thrust model, which is included in ship performance simulation models, is modified to improve the prediction of ship net thrust with any given set of propulsive setting.

The research question in this paper is how well the state-of-the-art methods predict ship resistance and speed in some of the most commonly defined ice conditions, e.g. level ice, ridged ice and channel ice, based on available full-scale data. The evaluation involves two aspects: the validation of selected methods and the identification of the most important uncertainties. The focus is on the global resistance and ship speed. Even though some of the studied methods also predict ice loads on the hull, the analysis of these is outside the scope of the current work.

Fig. 1 presents the structure of the methodological process applied in this work. The aim is to extract accurate information from extensive full-scale measurement data and use this to evaluate the performance of the selected state-of-art methods for ship performance in certain ice conditions. First, Section 2 reviews and analyses resistance prediction methods. After that, Section 3 presents the methodology of extracting accurate information with least uncertainties from full-scale measurement. Section 4 describes the test procedure for assessing the model performance relative to the full-scale data. Section 5 compares the prediction results by selected methods with measured data. In addition, it analyses and discusses the resistance components and the magnitudes. Section 5 also evaluates the uncertainties in the prediction due to assumptions or simplifications in modelling. Section 6 provides a discussion on the results and Section 7 summarises this paper.

2. Ice resistance prediction methods

This section presents an overview of the state-of-the-art methods for modelling ice breaking components and related phenomena affecting a ship's resistance in ice. The physical processes and the modelling approaches applied in previous studies are discussed. Several methods are selected for the comparison with full-scale data. The symbols used in the equations are summarised in Appendix A.

2.1. Level ice

The resistance from ships breaking level ice has been extensively studied via different approaches.

These approaches can be categorised according to the similarities in modelling the icebreaking sub-processes. Therefore, the investigation into some representative methods could give an overview on the benefits and drawbacks of a certain category of methods. Since level ice breaking involves a number of physical aspects, such as ice bearing capacity and breaking pattern, the investigation into the most critical aspects is necessary for understanding the uncertainties in the modelling approaches.

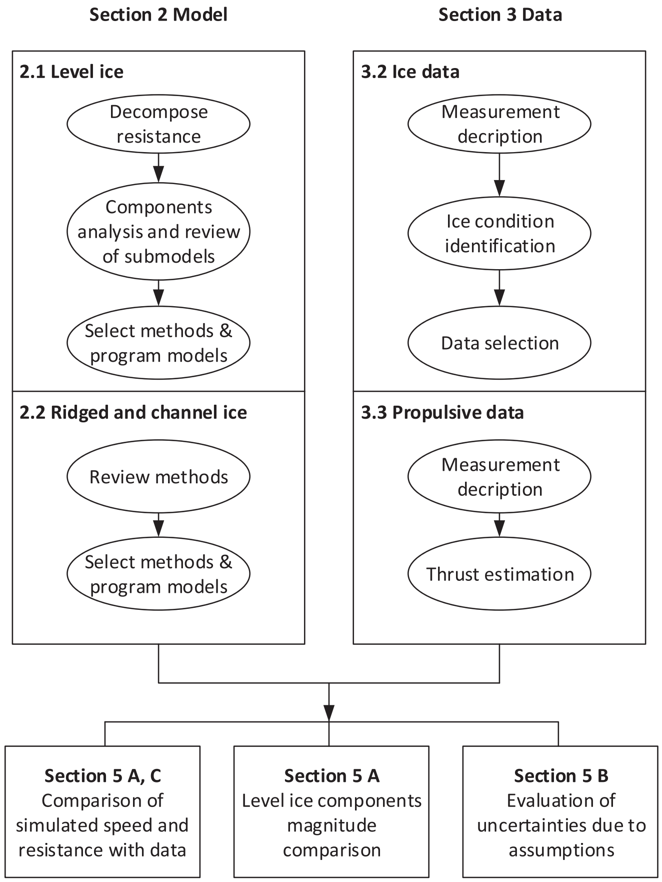

Fig. 1. Structure of the methodological process of this paper.

2.1.1. Methods review and analysis

Although many different methods have been proposed for ship resistance in level ice, their underlying logic is similar. The most common approach is to divide the resistance into components and sum these up. Physically, there are mainly three stages in the ship-ice interaction, which are generally modelled as being independent from one another. The first stage starts from the initial contact between a ship hull and the ice sheet and ends when an ice cusp breaks from the ice sheet due to crushing forces causing downward bending. This cusp is then rotated until it is parallel to the ship hull. After that, the cusp slides along the hull until it separates from the ship. Enkvist (1972) included rotation resistance in a separate speed-dependent resistance term. However, if the resistance components are divided in the sequential stages described above, accounting for ship speed as an influencing factor in each stage rather than as a separate component, the total resistance can be expressed as

$$R_t = R_b + R_r + R_s \tag{1}$$

where R_t is the total resistance; R_b, R_r and R_s are the breaking, rotation and submersion resistance. Lindqvist (1989) did not take rotation force into account but considered resistance as the summation of crushing, breaking and submersion resistance with speed effect. However, since the bending failure is caused by the downward component of crushing force, in some other models, e.g. Su et al. (2010), it is not considered necessary to separate the breaking force into crushing and bending components.

For modelling the breaking component, the bearing capacity of the