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Safety distance modeling for ship escort operations in Arctic ice-covered waters

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ABSTRACT

Melting of sea ice in Arctic areas has opened up new horizons for the development of Arctic Marine Transportation Systems (AMTS). An icebreaker assists a single ship if the ice classification of the ship does not meet the ice conditions. With the increase of the number of ships and escort operations, the risks of collisions between escorting ships (icebreakers) and escorted ships have also increased. In view of this, a calculation model of the safety distance and collision risks between escorting and escorted ships is proposed in this paper in order to facilitate safe navigation in Arctic ice-covered waters. The aim of the paper is to analyze features of navigation concerning icebreakers and escorted ships in escort operations under continuous icebreaking conditions, where a quantitative model is proposed to calculate safety distances under varying ice conditions based on the ship-following theory. The proposed model is able to quantify safety distance intervals at an acceptable collision frequency under varying ice conditions, as well as the movement characteristics of icebreakers and escorted ships. A case study is carried out to calculate the safety distance between "YONG SHENG" and "50 LET POBEDY". The results show that the model can accurately calculate the safety distance between "YONG SHENG" and "50 LET POBEDY", which can provide theoretical guidance for ice navigation.

1. Introduction

Recently, Arctic sea ice started to decline in volume, extent and thickness. This process has led to increased interest in Arctic activities of ships. The Northeast Passage (NP) is the shortest track between northern Europe and northeast Asia, which is approximately 40% shorter than the traditional Suez Canal Route (Schøyen and Bråthen, 2011). Many shipping companies try to use this sea route to decrease costs and times of trips (Fu et al., 2016; Zhang et al., 2016). Moreover, hydrocarbon resources in Arctic areas can be exploited and transported during such trips.

With the global warming and significant sea ice melting, the extremely valuable Northeast Passage greatly enhances the value of Arctic waters. However, since many ships lack the ability to break ice, they are unable to sail independently in the harsh ice environment, and need to be escorted, which easily leads to ice collision accidents (Kum and Sahin, 2015). Icebreaker assistance is a widespread method used in navigation in Arctic waters, where escort and covey operations are the crux to the success of the safe navigation of merchant ships. Icebreaker assistance is organized as usual in ship escorts or convoys. The number of ships in the convoy with one or more icebreakers depends on the ice concentration and ice thickness (Valdez Banda et al., 2015). For ships designed for navigation in Arctic ice-covered waters, icebreaker assistance is mandatory. The purpose of icebreaker assistance is that the icebreaker lays a channel across solid ice. This ice channel is filled with ice cakes (small ice floes), so that the navigation of the ship is easier than in pack ice (the ice resistance is lower in the channel).

Regarding severe ice conditions in the AMTS (Bergstrom et al., 2016), icebreakers usually break ice surrounding escorted ships, which results in collision accidents during such operations, due to fast speeds and short distances (Goerlandt et al., 2016). These accidents during icebreaker assistance occur often enough. Fig. 1 presents the statistics of various accidents that took place in Arctic ice-covered waters and caused damages to ships (Goncharov et al., 2011). It can be seen that the percentage of collisions exceeds 12%.

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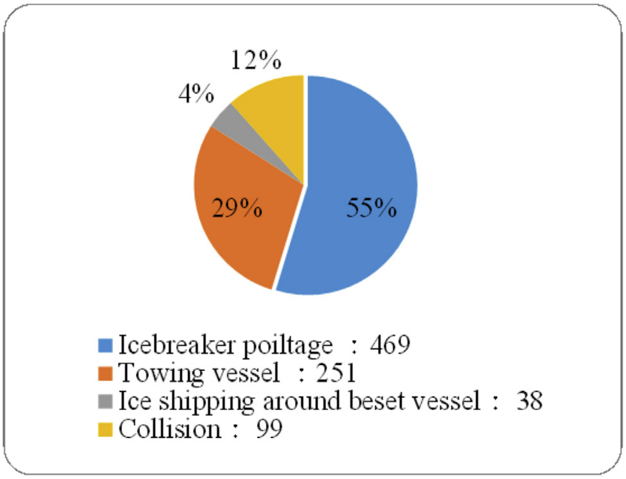

Fig. 1. Statistics of accidents involving ships under icebreaker assistance (Lobanov, 2013).

1.1. Literature review

The rules of navigation under icebreaker assistance have been developed and published in the Sailing Directions of Russia. The main requirement of the rules is the observance of the speed and distances between ships that the main icebreaker sets up for safe navigation. These requirements are applicable first to the ship moving after the icebreaker, because the icebreaker can stop and even move backward in especially hard ice conditions, for example, while meeting a ridge of hummocks.

The main determining factor of safety distances and speeds is the ice concentration. The higher the ice concentration, the smaller the safety distance, so that the ice channel does not close before the escorted ship.

- For the ice concentration of 4/10th–5/10th the safety distance is 1.5–2.5 cable length.
- For the ice concentration of 6/10th–7/10th the safety distance is 1–1.5 cable length.
- For the ice concentration of 8/10th–9/10th the safety distance is 1 cable length or even less.

There is a simple method of visible warning to prevent collisions of ships in escort operations. However, accidents of ships in such operations occur often enough.

In scientific literature, the risks of collisions are estimated to be higher in ice-covered waters than in open waters (Franck and Holm Roos, 2013; Sulistiyono et al., 2015). Recent risk analysis suggests that among collision accidents or incidents occurring under icebreaker assistance, escort and convoy operations are most dangerous in ice-covered waters (Valdez Banda et al., 2016; Goerlandt et al., 2017). This is because this kind of collision accidents in the AMTS may lead to several subsequent hazardous scenarios, such as hull damages, oil spill and wrecks. On the 20th of January 2011 at 0057LT, a collision happened between Swedish icebreaker ATLE and SALSA during icebreaker assistance at 65°05.1′5f026°41.0′1. The icebreaker ATLE was damaged to the rubber fender of the towing notch. The escorted ship SALSA got a 1,5 m hole in the port bow, and was also damaged to plating and frames. Moreover, the port anchor of the escorted ship was cracked (Franck and Holm Roos, 2013). The studies of the safety distance between an icebreaker and an escorted ship in ice-covered waters are helpful to reduce the probability of the occurrence of collision accidents. Regarding related works on the safety analysis of ice navigation and safety distances, Montewka et al. (2015) proposed a risk model based on a Bayesian Belief Networks (BBN) for predicting the probability of a ship getting stuck in ice. Collisions between escorted or following ships and icebreakers are the most important risk events. A root cause analysis method is presented to analyze the risks of collision and grounding in Arctic ice-covered waters, which indicates that short distances and high speeds are main risk factors contributing to accidents (Valdez Banda et al., 2015). The international code for ships operating in polar waters (the Polar Code) was adopted by the 94th Maritime Safety Committee (MSC) in 2014, in which ship speeds in Arctic ice-covered waters were recommended depending on diverse ice conditions and the ice classification of the ship. China Maritime Safety Administration presented guidance on Arctic navigation in the Northeast Route recommending safe distances between the escorted ship and the icebreaker (the Guidance on Arctic navigation in the northeast route, 2014). There is also research on ship domains and safety distances in open water or port conditions (Fujii et al., 1971; Weng et al., 2012; Kujala et al., 2013; Zhang et al., 2015) and during Arctic ice navigation (Kum and Sahin, 2015; Goerlandt et al., 2016). Fujii et al. (1971) first proposed the concept of a ship domain, and defined it as “the domain around a ship under way which most navigators of following ships would avoid entering”. With the rapid development of the shipping industry, which has greatly increased the ship density, water transportation has faced more complex problems, which cannot be solved if only the behavior of an individual ship is considered. Accordingly, some water traffic research applied the theory of traffic flow derived from the field of road traffic research. In particular, He et al. (2012) established a distance model of inland ships based on the ship-following theory. Wen et al. (2015) studied safety distances between LNG ships during berthing, and proposed an LNG ships anchorage safety distance model considering the risks of ship collisions. The ship-following theory is used to propose safety distance models for mega ships (Wu and Cheng, 2012) and in confined waters (Lee and Moon, 2014).

The above studies calculate safety distances for ships in specific waters (open waters or restricted waters) or for specific types of ships. However, the safety distance between an icebreaker and an escorted ship in ice-covered waters is rarely discussed. Ship escort and convoy operations in ice conditions are investigated using Automatic Identification System (AIS) data, where a sea ice model using historical navigational data for the Gulf of Finland is proposed with the focus on the ship domain size and the convoy speed (Goerlandt et al., 2016). Although the recommended safety distance is used for Arctic ice-covered waters, the safety distance for escort operations is not discussed with the focus on movement characteristics in different ice conditions using historical navigational data.

1.2. Objectives and contributions

The safety distance has been shown to be an important index to ensure safety and decrease collision risks between escorted ships and icebreakers in Arctic ice-covered waters. The study proposes a safety distance model for escort operations in ice-covered waters taking into account historical navigational data, ice data, ship classification etc. The model is based on the ship-following theory and an acceptable criterion of collision probability, in order to calculate the safety distance between the escorted ship and the icebreaker under an acceptable collision frequency. This study seeks to contribute to the existing literature in three ways. First, we collect and process historical navigational data in Arctic ice-covered waters, in order to select actual historical data on speeds and distances between escorted ships and icebreakers in different ice conditions according to their movement characteristics. Second, ships' movement characteristics, personnel management, and dynamic evolutions are analyzed. At the same time, coupling relations between speeds and safety distances are thereby established in different ice conditions. Finally, a model to determine risk acceptance criteria of ship collisions is proposed, which is based on the reality of risks of collisions. It is an effective way to reduce risks of ship collisions by establishing a calculation model of safety distances under icebreaker assistance.

The contributions and novelties of this paper lie in the development of the model of a safety distance metric between escorted ships and icebreakers, thereby quantifying the collision risk levels of different