Cold Regions Science and Technology 112 (2015) 14–28

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Towards probabilistic models for the prediction of a ship performance in dynamic ice

Jakub Montewka [a,*], Floris Goerlandt [a], Pentti Kujala [a], Mikko Lensu [b]

[a] Aalto University, Dept. of Applied Mechanics, Research Group on Maritime Risk and Safety, 02150, Espoo, Finland
[b] Finnish Meteorological Institute, 00560, Helsinki, Finland

ARTICLE INFO

Article history:
Received 19 March 2013
Received in revised form 20 November 2014
Accepted 20 December 2014
Available online 26 December 2014

Keywords:
Ship performance in ice
Bayesian networks
Machine learning
Ship beset in ice

ABSTRACT

For safe and efficient exploitation of ice-covered waters, knowledge about ship performance in ice is crucial. The literature describes numerical and semi-empirical models that characterize ship speed in ice. These however often fail to account for the joint effect of the ice conditions on ship's speed. Moreover, they omit the effect of ice compression. The latter, when combined with the presence of ridges, can significantly limit the capabilities of an ice-strengthened ship, and potentially bring her to a halt, even if the actual ice conditions are within the design range for the given ship.

This paper introduces two probabilistic, data-driven models that predict a ship's speed and the situations where a ship is likely to get stuck in ice based on the joint effect of ice features such as the thickness and concentration of level ice, ice ridges, rafted ice, moreover ice compression is considered.

To develop the models, two full-scale datasets were utilized. First, the dataset about the performance of a selected ship in ice is acquired from the automatic identification system. Second, the dataset containing numerical description of the ice field is obtained from a numerical ice model HELMI, developed in the Finnish Meteorological Institute.

The collected datasets describe a single and unassisted trip of an ice-strengthened bulk carrier between two Finnish ports in the presence of challenging ice conditions, which varied in time and space.

The relations between ship performance and the ice conditions were established using Bayesian networks and selected learning algorithms.

The obtained results show good prediction power of the models. This means, on average 80% for predicting the ship's speed within specified bins, and above 90% for predicting cases where a ship may get stuck in ice.

1. Introduction

Ship performance in ice has been given a lot of attention in the recent years, especially among northern maritime countries i.e. Canada, Finland, Norway, Russia and Sweden. However due to global warming resulting in the opening of the northern sea route in the Arctic, the issue becomes of global interest.

This increased attention has led to the development of semi-empirical methods that estimate ship resistance and ship speed in ice, see for example (Kotovirta et al., 2009; LaPrairie et al., 1995; Lapp et al., 1997; Lindqvist, 1989; Lubbad and Løset, 2011; Mulherin et al., 1996; Naegle, 1980; Riska et al., 1997; Su et al., 2010). However the ice conditions, which are considered in these models, are often limited to level ice and ice channel. In some cases, the effect of ice ridges is taken into account (Riska et al., 1997), (Juva and Riska, 2002), (Keinonen, 1996).

Further studies are required for example concerning the quantification of the joint effect of the relevant ice features on ship speed including the effect of ice compression (Kubat, 2012; Kubat et al., 2013; Kubat et al., 2015; Külaots et al., 2013; Tomac et al., 2013). Moreover, suggestions have been made to move from the deterministic, quantity-oriented models towards probabilistic and event-oriented models (Kotovirta et al., 2009). An event-oriented model reflects the ice features under which an event of interest occurs e.g. ship proceeding with certain speed or a ship getting stuck in ice, see for example E. T. S. Inc et al. (1996). This type of modeling, unlike the commonly adopted quantity-oriented approach, quantifies the joint effect of various ice features on ship's speed. However, it does not provide an insight into the physics of the process of ice breaking. Moreover, if appropriate probabilistic modeling techniques are applied, they lead to a model which is

* Corresponding author at: Aalto University, School of Engineering, Department of Applied Mechanics, Marine Technology, P.O. Box 15300, FI-00076 AALTO, Espoo, Finland. Tel.: +358 50 5916740.
E-mail address: jakub.montewka@aalto.fi (J. Montewka).

http://dx.doi.org/10.1016/j.coldregions.2014.12.009
0165-232X/

computationally fast, easy to validate and can be updated if new knowledge about the conditions/inputs is gained. Such models can be used for prediction of the vessel performance in an operational setting, or in e-navigation services, including route optimization.

This paper introduces two probabilistic, event-oriented models for predicting performance of a ship navigating in ice. In this paper we measure ship performance using two indicators. The first is the probability for a ship to attain certain speed (model A). The second is the probability for a ship being best in ice (model B). The following ice features are considered: thickness and concentration of various types of ice (level ice, ridged ice, and rafted ice), ice compression and its relative direction with respect to a ship.

To develop the models linking the ice field features with certain events which reflect ship performance in ice, machine-learning algorithms were applied to a predefined and carefully selected learning dataset. The latter contained full-scale data about performance of a certain ship in specific ice field along a specific route. This means a single and unassisted trip of an ice-strengthened bulk carrier between two Finnish ports in the presence of challenging ice conditions, which varied in time and space.

The learning dataset was obtained, by combining in a tempo-spatial fashion a set containing data about ice field, obtained from a state-of-the-art numerical ice model, called HELMI (Haapala et al., 2005), with a set describing ship performance in this ice field—obtained from the automatic identification system (AIS).

As a result, two probabilistic models were developed, a.k.a. Bayesian belief networks (BBNs). A major advantage of BBNs over many other types of predictive models, such as neural networks, is that the BBN's structure represents the inter-relationships among the dataset attributes in a probabilistic fashion. Moreover, if experts are involved in the process of model development they can easily understand the model structures and if necessary modify them to increase the predictive power of the models.

The remainder of the paper is organized as follows: Section 2 presents full-scale datasets used for the development of the models. Section 3 introduces the adopted modeling techniques. The developed models and the obtained results are shown in Section 4, and discussed in the following section. Section 6 concludes the paper and summarizes the main findings.

2. Data

The approach taken towards development of the probabilistic models presented in this paper, capable of forecasting ship performance in ice, utilizes techniques of Bayesian learning from data. These models first determine the relations between all the analyzed explanatory and response variables, and second they quantify the joint effects of ice features on ship's speed, allowing probabilistic analysis of ship performance in ice.

To develop the models, two data sources were used. First the reanalyzed ice forecast was taken, called hindcast, for the sea area under consideration. This dataset provides information about ice features for the interval of 1 hour and spatial resolution of 1 NM by 1 NM. Second, the database containing the state vectors of an analyzed ship was constructed. This included ship course and speed obtained from AIS, recorded with an interval varying between 2 sec and 3 min, depending on the speed of the vessel and operational status, see US Department of Homeland Security (2013). Then, these two datasources were matched in tempo-spatial fashion spacing equally the entries time-wise, and a database was created that reflected ship performance in dynamic ice over the analyzed time span. However such database required further analysis before it is used for modeling purpose, as the entries that may deteriorate predictive power of the models shall be removed. Such entries are: the time instances where a ship remains beset in ice for longer period or situations where changes in ship's speed are due to operational settings (ship navigating an ice channel, assisted by ice breaker or slowing down to board a pilot) not environmental conditions. In the first case, all the entries between the two time instants where a ship became beset in ice and she was released were removed, to keep only entries where the effect of ice features on ship's speed is observable. In the second case, videos were made, and experts were consulted to understand properly the analyzed voyage, identify and remove the undesired entries.

This resulted in the development of database, which contained 4040 rows, which are not equally distributed in time, but they reflect as far as possible the causality that exists between the environmental conditions and the performance of a ship. Therefore each row in the database comprises of 12 columns representing the following parameters—including two response variables:

1. ship speed [kn]—response variable,
2. ship beset in ice [yes/no]—response variable,
3. level ice concentration [%],
4. level ice thickness [cm],
5. ridged ice concentration [%],
6. rigded ice thickness [cm],
7. rafted ice concentration [%],
8. rafted ice thickness [cm],
9. relative direction of ice compression [deg],
10. ice compression magnitude [0–4],
11. relative direction of wind [deg],
12. wind speed [kn].

Finally, two learning algorithms were applied to the database to determine the models' structure and estimate the parameters. The obtained probabilistic models and their results are valid for a particular ship type, which is an ice going bulk carrier with ice class of IA Super—see Table 1—which is navigating under a certain set of hydrometeorological conditions.

2.1. Date and area of interest

The date and area of interest have been selected specifically to capture challenging ice conditions, meaning high concentration of level ice, the presence of ridged ice and ice compression that changes in time. For this reason, the day of 6th of March 2011 was chosen, and the sea area between two Finnish harbors, in the Bay of Bothnia (the Baltic Sea), namely Vaasa and Kokkola were selected. The case study presented here is based on records of a single trip of the bulk carrier between two positions of boarding a pilot, meaning that the stage of the high-seas navigation is considered, where the ship is supposed to proceed with full engine power. In Fig. 1 the trajectory of the ship is overlaid on the ice chart, therein the ship track is marked with the blue circles, whereas the locations where the ship was brought to a halt are marked with yellow crosses.

The ship covered a distance of 94 NM in 14 hours, and the ice conditions hampered her significantly, making her ram the ice several times, and forced her to idle in ice for three hours. The recorded data contain significant variability and strong effect of environmental conditions on ship's speed, as depicted in Fig. 2, thus the created dataset can be considered appropriate for the model development.

Table 1
Ship particulars.

Type	Bulk carrier
Ice class	IAS
DWT	21353 t
Length	149.3 m
Breadth	24.6 m
Draught	9.4 m
Power	9720 kW
Year of construction	2006