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A generalized probabilistic model of ice load peaks on ship hulls in broken-ice fields

A. Suyuthi [a,*], B.J. Leira [a], K. Riska [b,c]

[a] Department of Marine Technology, NTNU, Trondheim, Norway
[b] Centre of Ships and Offshore Structures (CeSOS), Trondheim, Norway
[c] ILS OY, Helsinki, Finland

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ABSTRACT

On some occasions, especially when traveling in a broken ice field, the process of ice induced loads on ship hulls cannot be well modeled by traditional statistical models which are usually applied for this purpose. Examples of such are the one-parameter exponential and the Weibull's models. The fitting achieved by application of these models could generally result in underestimation of the predicted extreme values. Therefore a so-called generalized model, i.e. the three-parameter exponential model, is proposed in order to improve the process of fitting. The proposed model is actually a proportional combination of two one-parameter exponential models. It tends to give more conservative predicted extreme values as compared to the one-parameter exponential and the Weibull's models. Various approaches for estimation of the parameters are treated, i.e. the method of moments, the non-linear least square method, the non-linear least square method based on application of Kernel density estimation, and the maximum likelihood estimators. The fitting by means of the non-linear least square method was observed to give the best results. However, more stable predictions are provided by the maximum likelihood estimators.

1. Introduction

In contrast to the wave surface elevation, which is usually well represented by a Gaussian process, the magnitude of the ice load acting on ship hull cannot in general be modeled by a specific well-established probability distribution. The irregular variation of the wave surface elevation can be modeled by expressing it as a sum of regular waves with varying amplitudes and frequencies, see Ochi (1998). Based on the central limit theorem, the resulting value at a specific point in time can be modeled by the Gaussian's distribution. Theoretically, this property is well justified and has also been confirmed by consideration of measured wave records. Representation of the ice induced load as a random process is much more involved. At present it does not seem to be any strong physical or mechanical justification for selection of a particular statistical model.

Therefore, previous work has focused on the classical statistics with much effort associated with fitting the ice induced load process to existing statistical models. Two models were identified as providing an adequate representation of the ice induced load process, i.e. the exponential and the Weibull's distributions, see e.g. Jordaan et al. (1993), Kujala and Vuorio (1986), Kujala et al. (2009), Suominen and Kujala (2010) and Suyuthi and Leira (2009). Even though proper procedure has been applied for the fitting, and the goodness-of-fit test showed that the fitted model could be accepted, the restricted shapes of the well-established distribution models seem to be inadequate for some of the data.

On some occasions, especially when traveling in a broken ice field, the recorded data deviate somewhat from the model, both for the exponential and the Weibull's distributions. Here, broken ice field is an ice covered sea which almost "all types" of ice exist, such as level ice, ridges, re-frozen ice, hummock, and also open water. Kujala et al. (2009) also mentioned that the one-parameter exponential model fits to the entire distribution only in rare cases. An example is given in Fig. 2 for both these distribution types. The scatter plot is the empirical c.d.f., while the straight lines are the estimated models, which are formulated for the exponential and Weibull's model as follows:

$$F(y) = 1 - \exp(-\lambda y) \tag{1}$$

$$F(y) = 1 - \exp\left\{-\left(\frac{y}{\theta}\right)^k\right\}. \tag{2}$$

The ice induced load data used in Fig. 2 was deducted from the record shown in Fig. 1. The particular time interval of the record in the figure was selected due to its stationary characteristics with respect to the ship's propulsion power, see Fig. 1B. However, the speed over ground for this particular time interval seems to be quite variable ($RSD = 16\%$) and tends to be strongly affected by the variation of the

* Corresponding author at: Arctic Technology, DNV Research and Innovation, DNV GL, Høvik, Norway.
E-mail address: abdillah.suyuthi@dnv.com (A. Suyuthi).

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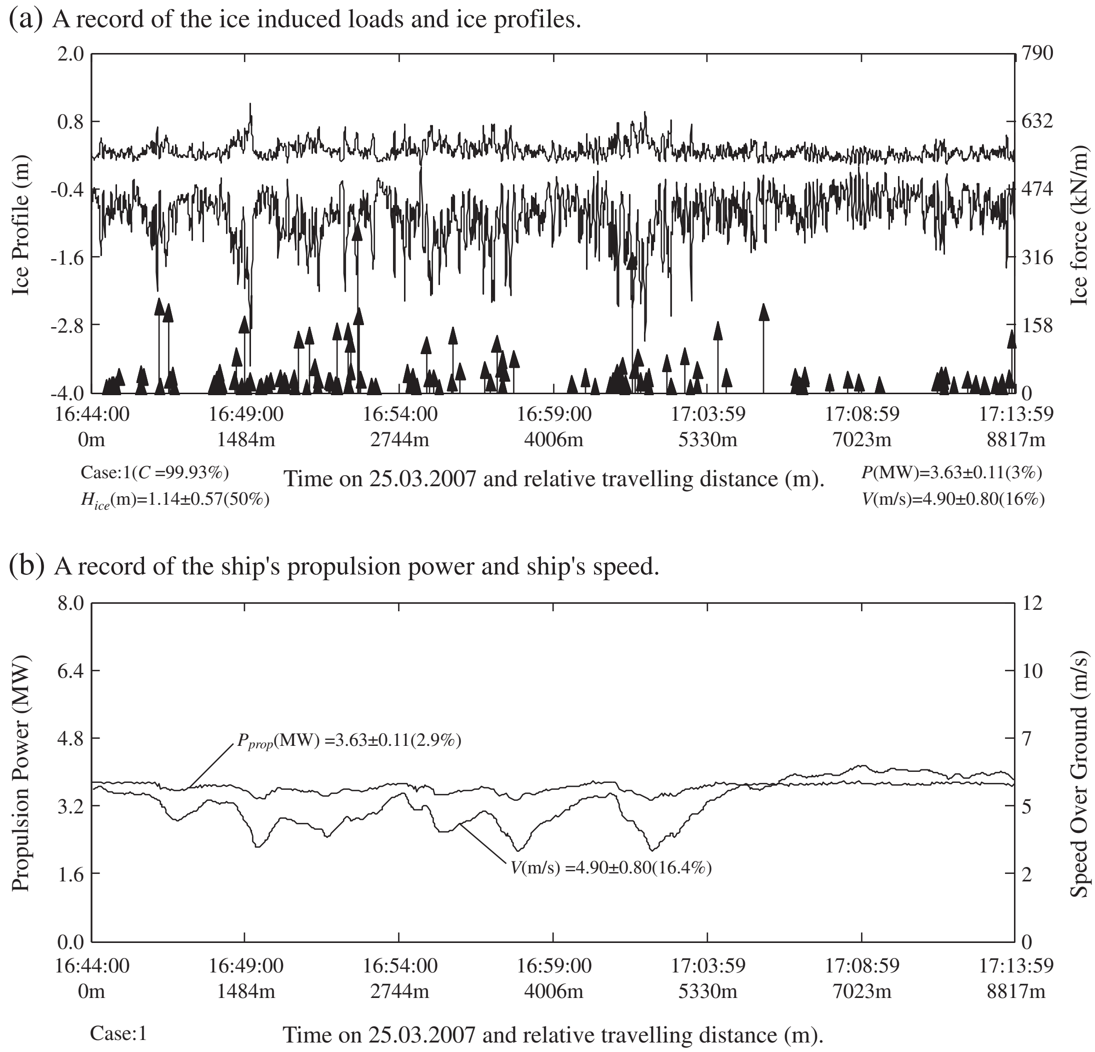

Fig. 1. An example of a record of the ice induced load, ice thickness, ship's propulsion power, and ship's speed for a particular time interval. These measured data were obtained on board KV Svalbard during its expedition in the winter 2007.

prevailing ice thickness. These measured data were obtained on board KV Svalbard during its expedition in the winter 2007.

Fig. 2 shows that even for the models providing the best fits as suggested by previous works, i.e. the exponential and the Weibull's distributions, some data points are not properly reflected by the estimated model. In Fig. 2A and B, both the lower and upper tail data (with the latter being important for the largest extremes) are not appropriately fitted by the estimated models. There is an important note for the upper tail fitting to the Weibull's distribution which looks like to be just fine as shown in Fig. 2. It is clear that somehow the fitting put more weight in the middle part. This should be fine if the model will be utilized to predict fatigue damage of which most of the load is concentrated at the middle. However, as can be demonstrated later in the present paper, the fitted distribution could result in underestimated extreme values. Therefore, an alternative model is needed. These observations give enough reason to pursue a non-parametric approach, see e.g. Suyuthi et al. (2012).

Applying the non-parametric approach, the estimated distribution will be free from prior assumptions related to the underlying (well-established) model and will be strongly characterized by the data. Suyuthi et al. (2012) applied the Kernel density estimation and observed that in most cases the non-parametric approach gives more conservative extreme values. It seems that the upper tail data points, even though quite rare, contribute significantly to the fitting of the extreme distribution in contrast to the parametric approach (the one parameter exponential model and the Weibull's model), which puts more focus on the bulk of the data in the lower tail region.

Although the non-parametric statistical approach seems to be promising for estimation of the extreme value of ice-induced loads by providing a better fit to the data, there is still a drawback. The non-parametric approach depends strongly on the available data. Hence, it is adequate for application in relation to on-line direct estimation of the short term extreme ice load. This is relevant, e.g. in connection with Ice Load Monitoring (ILM) systems. However, it is not possible to relate such a prediction to the prevailing ice condition and ship voyage characteristics. Accordingly, this cannot be applied for prediction related to other conditions during the service life of the ship and the associated long-term distribution. Hence, a parametric generalized model is needed.

This paper proposes a three-parameter exponential model as a parametric generalized model for the ice induced load. The proposed model is actually a combination of two exponential distributions with proportional factors. The concept of implementing a combination of two exponential distributions for representation of the ice-induced load process is new. However, the concept of mixtures of distributions is not new. Sinha and Kale (1980) in their book applied such mixtures of distributions to model more complex failure time processes. The presented approach of utilizing the combination of two exponential distributions was initiated when observing the probability plot of ice-induced load data in exponential probability paper of which