Proceedings of the 22nd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2013
Espoo, Finland

A SIMPLIFIED ICE LOAD MODEL FOR ASSESSING THE GLOBAL DYNAMIC RESPONSE OF SHIPS

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ABSTRACT

A simplified ice load model applied on ship hull is developed, which can be used to assess the global dynamic response of a ship cruising in level ice. Full scale ice load time histories acting on the local positions along the hull are estimated using the strain data measured on the frames. It is found that the correlations between local loads are negligible, thus the focus is put on developing a simple model to simulate the loads on the local segments along the hull. In order to assess a ship's global dynamic response, the local ice loads are independently simulated using this model and then applied along the hull. Based on statistical analysis of the full scale data, the model in time domain is developed, which depends on the hull geometry, cruise speed and ice thickness. Some simplifications are made in the present model, which can be improved in the future. By Fourier transform of typical ice load time histories, a power spectral density function is developed, which is the equivalent model of the local ice load in frequency domain.

1. INTRODUCTION

In the Arctic or sub-arctic waters, ships must have the capability of breaking the thick ice floes. The research on ice resistance of ships has been performed for a long time, and representative findings have been published (e.g. Lindqvist, 1989). Various approaches have been used to improve the understanding of ice-hull interaction. In order to obtain the first hand information, full scale ships are instrumented to measure the ice loads on ship hull (e.g. Hänninen, 2003. Kujala, et al., 2009. Iyerusalimskiy, et al., 2011); Because of the much lower cost and more complete dataset, model tests have been used a lot in spite of the scaling effects (e.g. Izumiyama, 2005, Kujala, et al., 2012); On the other hand, numerical models have been developed in recent years (e.g., Su et al., 2010, Lubbad et al., 2011). Most of the research activities so far concern the prediction of ice resistance and the strength of hull against ice loads, and there is limited work on dynamic characteristics of the ice loads.

Ships going through ice might experience vibration under ice loads, but in most cases this is not a critical problem since the local ice loads along the hull vary non-simultaneously, and the dynamic component of the global resultant ice load is insignificant. However, for some types of ships which might be vulnerable to global dynamic response, the potential risk of global ship vibration should be assessed, which is the main intention of this paper. A simple model is developed to simulate the time-varying ice load acting on ship hulls, and the basis is a set of strain data measured on the frames of a full-scale ship. The strain data is used to estimate the load acting on local segments along the hull, and the concurrently recorded ice thickness and ship speed are used to calibrate the parameters in the model.

2. ICE LOAD DATA AND INDEPENDENCE BETWEEN LOCAL LOADS

The data used in this paper comes from a cruise of Norwegian coast guard ice breaker KV Svalbard (Figure 1) in March 2007, and the vessel was instrumented with a set of equipment to collect all kinds of information. A number of strain sensors were mounted on the frames of the ship close to waterline, and the intention is to estimate the ice load acting on the local segments of the hull. The strain sensors were located on nine different locations along the hull (Figure 1), and the distance between adjacent locations is about 4~6 m in the bow area. The original sampling frequency of the strain sensors were 678 Hz, which is proved as too high in the post-processing because of the high-frequency noise introduced. Therefore, the sampling frequency of the raw data is scaled down by a factor of 4, and the output sampling frequency is 168 Hz.

Figure 1 Photo of KV Svalbard and plan view of the locations of strain sensors

Considering an instrumented frame as a beam, the strain signal can be used to estimate the shear force in the beam, which is then used to approximate the ice load acting on the local area. Even though numerical calibration is done using finite element model of the local hull component, the accuracy of ice load estimating was still unsatisfactory (Espeland, 2008). In spite of this uncertainty, the estimated ice loads are still used in developing the present model, because the model intends to have a dimensionless form and the effect of load magnitude can be eliminated. When applying the model, the load magnitude needs to be estimated separately.

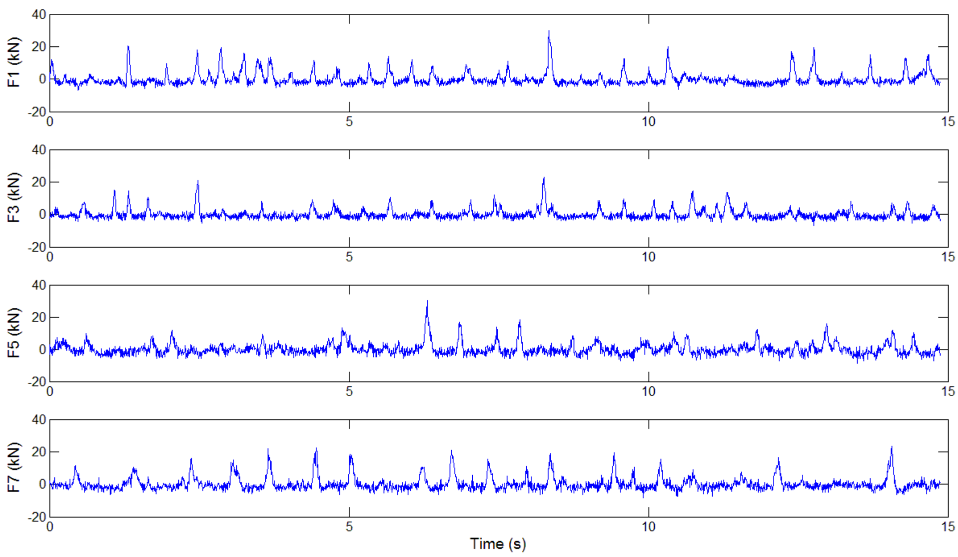


Figure 2 Local ice loads acting on the portside

Along with the strain data, ice thickness is recorded with sampling frequency of 15 Hz and cruise speed is recorded once a second. These two data sets are very important since the characteristics of ice load must be dependent on them. Totally 33 data events are used to develop the model herein, in which the ice thickness range is recorded as 0.2 ~ 2.0 m, the cruise speed range is 2.6 ~ 6.1 knots (Espeland, 2008). Figure 2 and Figure 3 show the ice load time histories in a typical event, in which the denotations of F1, F2, …, F8 correspond to the locations shown in Figure.1. Accordingly, F1, F3, F5 and F7 are the local loads acting on the portside and F2, F4, F6 and F8 act on the starboard. Since the instrumentation at mid ship location F9 is just for comparison and the load magnitude is significantly lower, F9 is not used in the analysis.

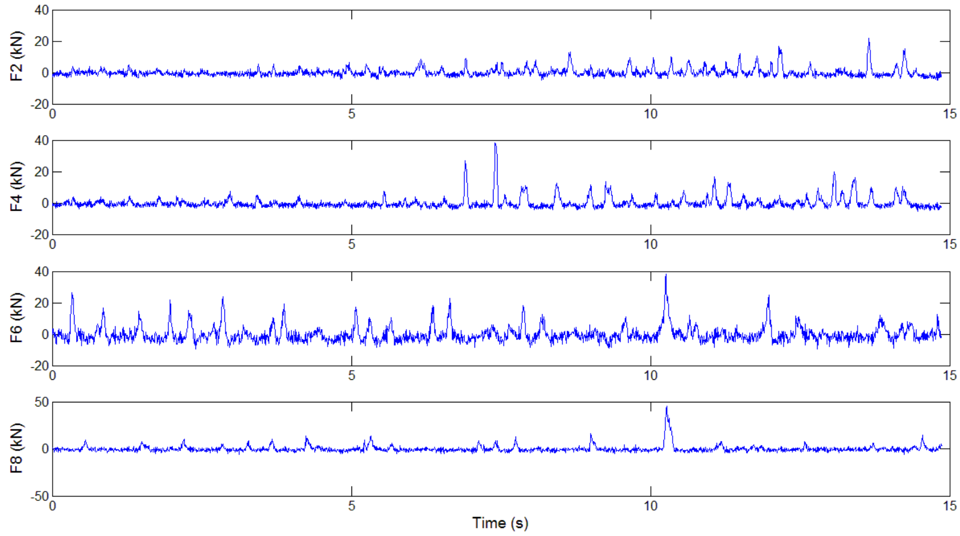


Figure 3 Local ice loads acting on the starboard

According to the concurrent time history plots in Figure 2 and Figure 3, the local ice loads on hull are a set of impulses and the loads on different locations do not fluctuate simultaneously, which means that the local loads might be independent to each other. For the purpose of investigating the independence of local loads, ten events are used to calculate the correlation coefficients between two local loads, and the result is shown in Figure 4.

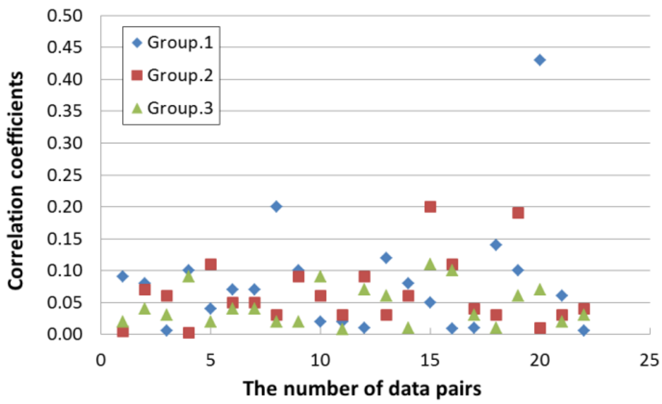


Figure 4 Correlation coefficients of the local loads

Referring to the denotations in Figure 1, the correlation coefficients are classified into three groups: Group.1 includes the correlation coefficients between two adjacent pairs, e.g. F1-F3, F5-F7 or F4-F6; Group.2 includes the correlation coefficients between two pairs whose distance is two times the adjacent distance, e.g. F1-F5, F3-F7 or F4-F8; Group.3 contains the correlation coefficients between the two pairs F1-F7 and F2-F8. The correlation coefficients indicate that there is little correlation between the local ice loads, which means that the local ice loads can be considered as independent if the distance between them is higher than 4~6 m.

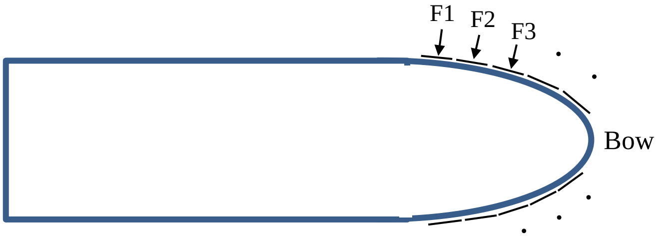


Figure 5 Sketch of independent local ice loads acting on virtually divided ship hull

The result in Figure 4 indicates that the correlation between measured local loads is negligible. As mentioned above, the distance between two adjacent measuring locations is 4 ~ 6 m, so that 4 m can be used as a conservative value for the parameter defined as "characteristic width". This characteristic width is used to determine the ice-hull contact area on which the local ice load is completely independent. The independence might still exist within area narrower than 4 m, but 4 m is chosen to exaggerate the simultaneity of local loads and the global dynamic ice loads on the hull. Accordingly, the methodology is to virtually divide the bow area by widths equal or higher than the characteristic width 4 m (shown in Figure 5), and then the ice loads are simulated independently on the virtual local areas. The simulation model is developed in the next sections.

3. LOCAL ICE LOAD MODEL IN TIME DOMAIN

As shown in Figure 2 and Figure 3, the basic pattern of the ice loads acting on local areas of hull is a series of impulses in time domain. Therefore, the ice load time history can be simplified as the model shown in Figure 6. There are three parameters in the model: F denotes the magnitude of the load impulse; T denotes the period between two adjacent impulses; T_I denotes the duration of a single impulse.

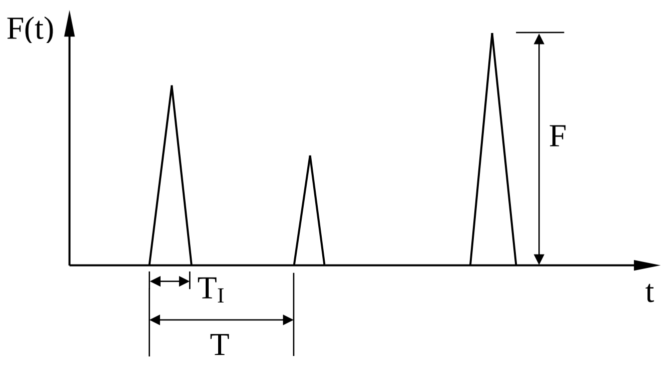


Figure 6 Idealization of the ice load time history

It is obvious that the three parameters in the model of Figure 6 are not deterministic, which is mainly attributed to the complexity of ice-hull interaction. It is assumed that the statistical characteristics of these parameters keeps stationary, given the ice thickness *h* and ship cruise speed *v*. In order to study the statistics of the three parameters, all the 33 data events with different *h* and *v* are analyzed. A program is developed to identify the magnitudes of load peaks and the periods between two adjacent peaks, and Figure 7 shows an example of identified load peaks from the load time history.

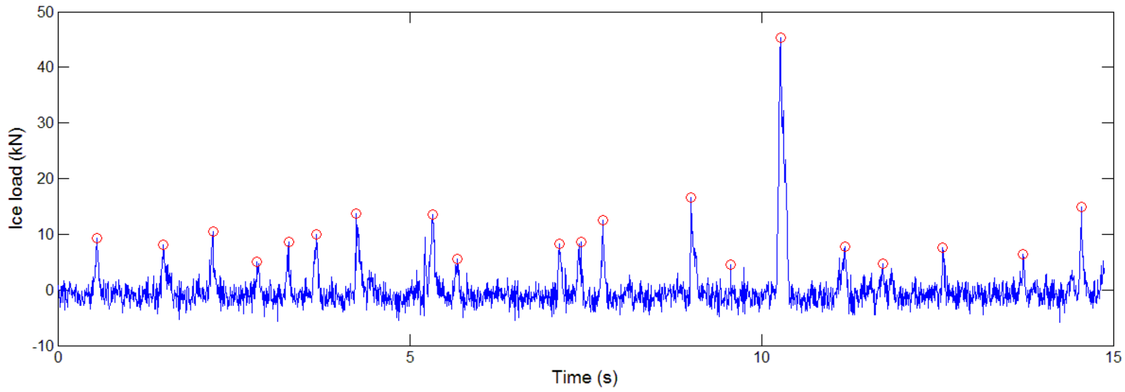


Figure 7 Identified peaks in an ice load time history

Ideally, with the simplified model in Figure 6 and statistics of the three parameters, the local ice load acting on hull can be simulated and applied on areas limited by characteristic width 4 m. However, the remaining question is: given the ice conditions and ship speed, how to predict the characteristic values (mean value, deviation, etc.) of the three parameters. This is discussed as follows.

Figure 8 is a simplified 2D sketch of ice interacting with ship hull, in which L_b is a variable defined as "breaking length" of ice sheet, and V_i denotes the relative interacting speed between ice and hull. Theoretically, the period *T* in the model Figure 6 should be proportional to L_b / V_i. The period *T* can be expressed as Eq. (1).

$$T = L_b / V_i \tag{1}$$

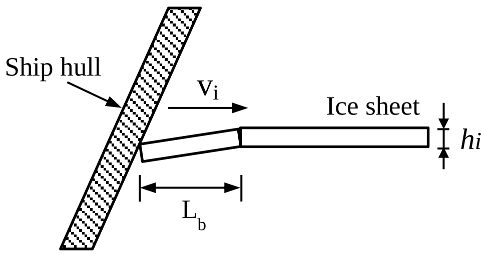


Figure 8 Sketch of ice breaking length and interaction speed between ice and ship hull

In reality, the hull segment has 3D geometry and the interaction configuration is more complex. There has been research on the breaking length L_b and relative speed V_i (e.g. Wang, 2001), in which L_b is proportional to $h_i^{3/4}$ and also dependent on V_i. In the present model it is simplified that L_b is proportional to h_i and the dependence on V_i is neglected. The basis of the simplification is mainly the statistical analysis of ice sheet breaking on sloping structure (Qu et al., 2006), and more accurate model by e.g. Wang (2001) can be introduced in the future improvement.

On the other hand, the relative interacting speed V_i is supposed to be proportional to ship cruise speed v. In this simplified model only the condition of ship going forward is considered, so that the linear relation between V_i and v only depends on the local locations along the hull. Accordingly, Eq. (1) is transformed to Eq. (2).

$$T = kh/v \tag{2}$$

As discussed above, the factor k covers the two approximate linear relations ($L_b \propto h$ and $V_i \propto v$). Naturally, k is a random parameter and the values should be different at different locations along the hull, but in this model it is simplified that k follows the same statistical characteristics. Considering that the intention of this model is to assess the global dynamic response of the ship, using only one statistical distribution of k for all the hull segments will exaggerate the global dynamic ice load, and the global dynamic response becomes conservative to some extent.

In order to investigate the range of k, the values of T are extracted from all the 33 data events with known h and v. The calculated values for k are plotted in the histogram Figure 9, in which the ordinate is relative frequency of occurrence. A log-normal distribution function is used to fit the probability density of the factor k, which is shown in the curve in Figure 9.

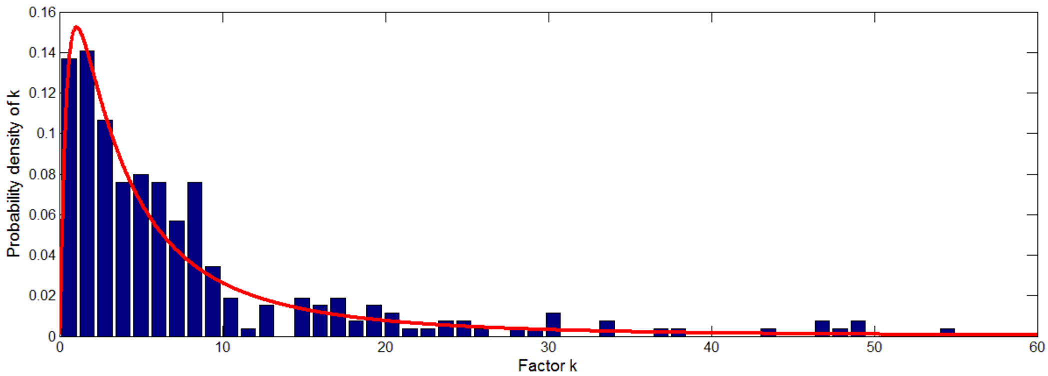


Figure 9 Probability distribution of the factor k

The log-normal probability density function (PDF) of the factor k is expressed by Eq. (3). Applying this PDF the expected value for the factor k is calculated as E[k] = 7.7

$$p(k) = \frac{1}{k\sigma\sqrt{2\pi}} e^{-\frac{(\ln(k)-\mu)^2}{2\sigma^2}} \qquad \mu = 1.5, \quad \sigma = 1.2 \tag{3}$$

Therefore, with the distribution Eq. (3) and the given h and v, a series of values for the period T can be simulated using Eq. (2), which are used to generate random ice load time history like the model of Figure 6. Another key parameter in the model Figure 6 is the load magnitude F, which depends on the inclining angle of hull, bending strength of ice, etc. A lot of efforts have been made on this topic (e.g. Kerr, 1975, Kujala, 1994). Since the intention of this simplified model is to investigate the resultant dynamic load, which depends on the simultaneity of local ice loads, the magnitude of local ice loads F is not the main concern. An approximate method is applied here to consider the ice edge as a cantilever beam, as sketched in Figure.8. Therefore, the beam has a length of the breaking length L_b and the beam's width w is assumed to be the width of virtual local hull area (characteristic width 4 m or higher). According to the theory of cantilever beam undergoing both vertical and horizontal force, the ultimate bending strength is estimated as:

$$\sigma_f = \frac{6F_V L_b}{wh^2} - \frac{F_H}{wh} = \frac{6F_V k}{wh} - \frac{F_H}{wh} \tag{4}$$

In which F_V denotes the maximum vertical ice force and F_H is the maximum horizontal force. According to ISO 19906 (2010), the theoretical relation between vertical and horizontal force on slopping structure is:

$$F_H = \xi F_V, \quad \xi = \frac{\sin\varphi + \mu\cos\varphi}{\cos\varphi - \mu\sin\varphi} \tag{5}$$

In which φ is the inclining angle of hull against horizontal, and μ is the friction coefficient between ice and hull. Substituting Eq. (5) into Eq. (4) the maximum horizontal force F_H is:

$$F_H = \frac{\xi wh\sigma_f}{6k - \xi} \tag{6}$$

Therefore, Eq. (6) is used here to estimate the load peaks F in Figure 6. It should be noted that Eq. (6) is not valid if the angle φ is high, in which case the crushing mode is dominant instead of bending. So far the load period T can be simulated using Eq. (2) and load magnitude F can be simulated using Eq.(6). It is noted that all the other parameters except k are either given (e.g. h, v) or can be determined as a typical value (e.g. ice bending strength σ_f). The random factor k follows the distribution Eq. (3), but it has to be emphasized that there is no statistical correlation between T and F, so that the values of k for T and F must be simulated independently.

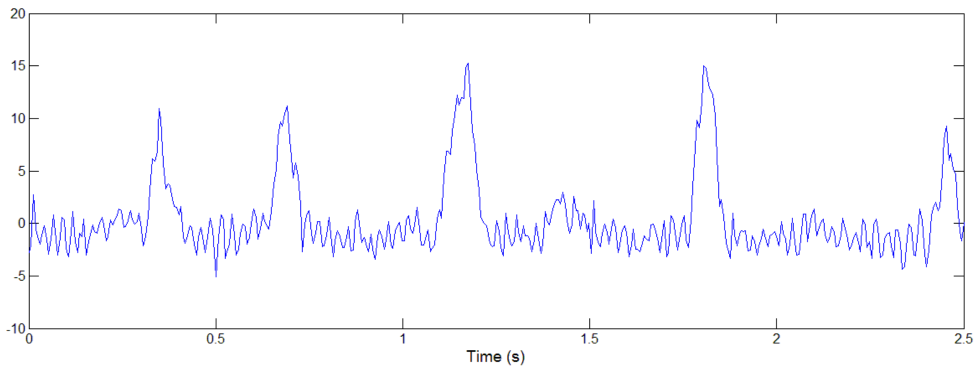


Figure 10 An example of ice load peaks duration

There is still another parameter T_I in the model Figure 6, which is the duration of one load impulse. From the point of dynamic response under ice load like Figure 6, T_I has much smaller effect than T, because T_I has little effect on the frequency distribution of ice load, so that the analysis of T_I is simplified here. Preliminary analysis of the 33 data events indicates that T_I has no obvious dependence on T or v or other variables. It is found that T_I lies in the range of about 0.1 ~ 0.5 seconds, and Figure 10 shows an example of load time history with $T_I \approx 0.1$ s. It is assumed here T_I is a random parameter which follows uniform distribution from 0.1 to 0.5 seconds.

As a summary, the methodology of the time domain ice load model is: firstly divide the bow area of ship hull into local segments like Figure 5 (the widths w = 4 m or a bit longer, depending on the dimension of the hull); and then for each local segment the ice load time history is independently simulated using Eq.(2), (3) and (6), the parameter T_I is set as a random variable following uniform distribution from 0.1 to 0.5; finally all the simulated local ice loads are applied along the ship hull to analyze the ship's dynamic response.

4. SPECTRAL MODEL OF THE ICE LOAD

Because the ice load model shown in Figure 6 is an irregular process which depends on several random parameters, it is interesting to investigate the load model in frequency domain. A spectral model is developed and described in this section, and all the 33 selected data events are used for the analysis.

In each event, firstly the power spectral density (PSD) is calculated for the eight local ice loads in the bow area (F1 ~ F8), so the PSD as a function of frequency *S(f)* is obtained. Figure 11 shows a typical PSD as a function of frequency (the fluctuating blue curve), and this original PSD is averaged to reduce the fluctuation (the smooth red curve). The frequency increment of the averaged PSD is 0.37 Hz.

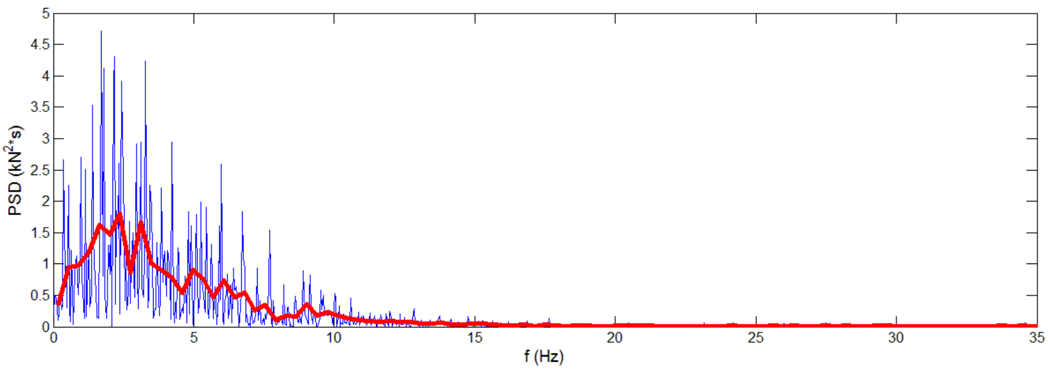


Figure 11 An example of original power spectrum density and averaged values

The absolute values of PSD like the example in Figure 11 are dependent on ice load magnitude F and period T in Figure 6. In order to eliminate these effects, a linear transform is performed to make the PSD function dimensionless, as expressed as follows.

$$\tilde{S} = \frac{S(f)}{\overline{F}^2\,\overline{T}}, \qquad \tilde{f} = f\,\overline{T} \tag{7}$$

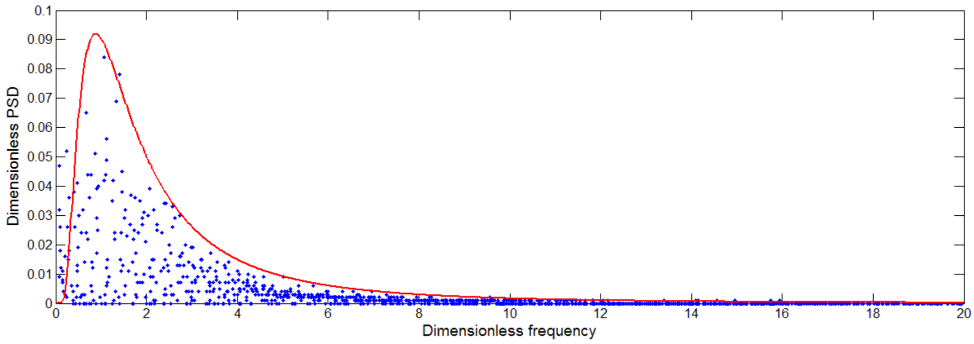
In which:

S	Original power spectral density;
f	Original frequency vector;
$\tilde{S}$	Dimensionless power spectral density;
$\tilde{f}$	Dimensionless frequency vector;
$\overline{F}$	Mean value of the ice load peaks F shown in Figure.6;
$\overline{T}$	Mean value of the ice load periods T shown in Figure.6

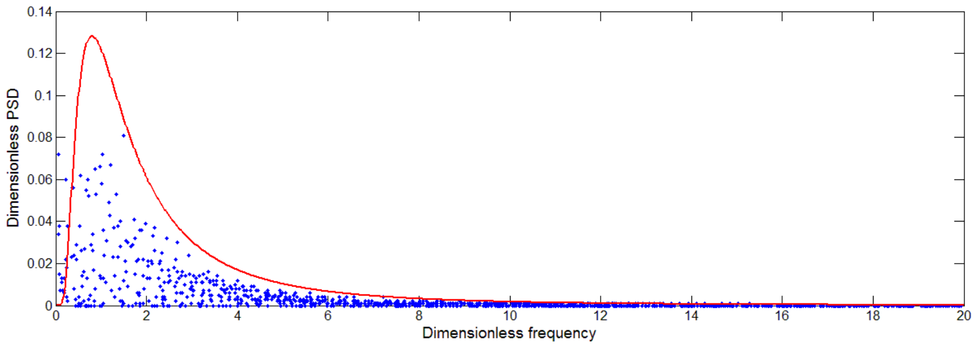
Because the transformed PSD function Eq. (7) is dimensionless, ideally it should be the same in all the measured data events, but the calculated results are still scattered due to imperfect stationary statistical characteristics in the measured data. Figure 12 shows the dimensionless PSD values calculated from the 33 events (the dot plots). Due to the symmetry of ship hull, it is assumed that F1 and F2 denoted in Figure.1 have the same statistical characteristics, and the assumption is similarly valid for the pairs F3-F4, F5-F6 and F7-F8. Eq. (8) is used to fit the dimensionless spectra, trying to cover all the spectra data points, and the fitting curves are also shown in Figure 12.

$$\tilde{S}(\tilde{f}) = \frac{A}{\tilde{f}^{p}} \exp\left(-\frac{B}{\tilde{f}^{q}}\right) \tag{8}$$

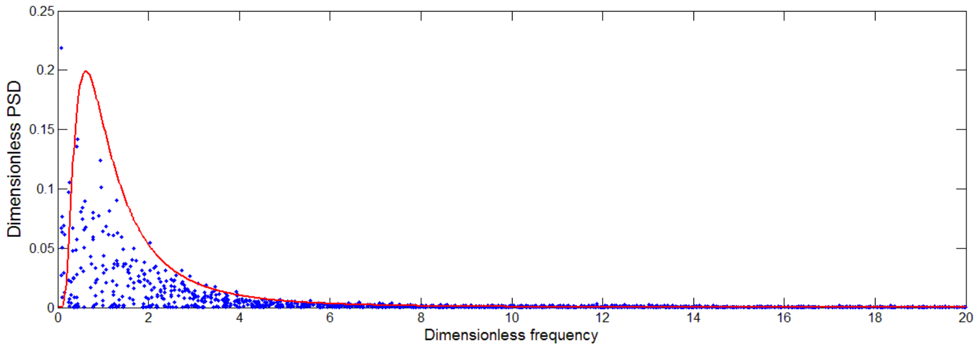
Eq. (8) includes four fitting parameters (A, B, p, q), and Table 1 lists the values of the four parameters for the local ice load pairs. The results indicate that there are slight differences among the fitting parameters for the four local load pairs, which are also shown in the red curves in Figure 12. However, it seems there is no obvious dependence or trend in the differences, so it is recommended that the dimensionless PSD containing the maximum power (the integral with respect to dimensionless frequency) is used for all the local hull sections, regardless of the local hull geometry. It is found that the parameter set for the load pair F7-F8 leads to the maximum power of dimensionless PSD.



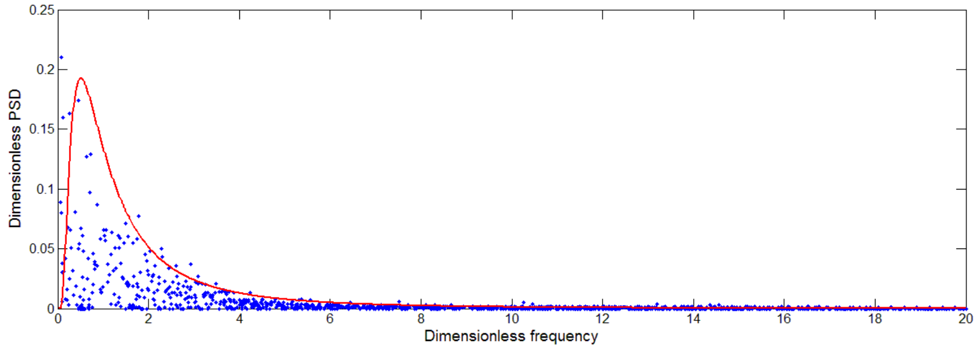
(a)



(b)



(c)



(d)

Figure 12 Dimensionless PSD and fitting results for the four local ice load pairs. (a) pair F1-F2; (b) pair F3-F4; (c) pair F5-F6; (d) pair F7-F8.

Table 1 The fitting parameters for the four local ice load pairs

Parameters in Eq. (8)	A	B	p	q
F1-F2	20	5.4	3.5	0.6
F3-F4	20	5.1	3.5	0.6
F5-F6	23	5.0	4.0	0.6
F7-F8	20	5.0	3.5	0.5

Therefore, Eq. (8) with parameters A = 20, B = 5, p = 3.5 and q = 0.5 is recommended as the dimensionless PSD function. In order to obtain the real PSD function $S(f)$, the inverse transform of Eq. (7) is needed, in which the two parameters $\overline{F}$ and $\overline{T}$ are calculated using Eq. (6), Eq. (2) and the expected value E[k] = 7.7 according to Eq. (3). In summary, the spectral model $\tilde{S}(\tilde{f})$ or $S(f)$ is equivalent to the time-domain load model described in the last section, and it shows the load's energy distribution in frequency domain.

CONCLUSIONS AND FUTURE IMPROVEMENT

The intention of this paper is to develop a simplified model enabling engineers to assess the global dynamic response of a ship going through level ice sheet. The measured data from a full scale ship is analyzed and the following simplifications are made:

1) The ice loads acting on the characteristic width 4 m on the hull is assumed to fluctuate simultaneously;
2) The local breaking length of ice sheet is approximated as proportional to ice thickness;
3) The periods of local ice loads follows one statistical distribution, which is proportional to the ratio between ice thickness and ship cruise speed.

The consequence of these simplifications is that the simultaneity of local loads is exaggerated and the resultant global dynamic response is conservative. As mentioned in the paper, many existing models can be introduced to improve the accuracy of the parameters in the model, which capture the spatial variation along the hull: the effect of local hull geometry, the effect of ship speed, and the effect of relative moving direction of ship, etc.

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