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UNCERTAINTY OF A METHODOLOGY TO ESTIMATE GLOBAL SHIP LOADS DURING INTERACTION EVENTS WITH ICE FEATURES

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ABSTRACT

This paper describes a methodology to estimate uncertainty of global ice loading from measured accelerations, velocities and displacements. The global load can be estimated by the principle of rigid body dynamics of the ship during interaction events with different ice features. The accuracy of the methodology and estimated load levels were studied with uncertainty analysis. The challenges for the global load calculation from ship motions and challenges related to the uncertainty analysis are discussed extensively.

An example case of global ice load and its uncertainty calculated from ship motions is presented. Ship motions in six degrees of freedom were measured using a motion reference unit during interaction events with different ice types during the ice trials of South African research icebreaker S.A. Agulhas II in the Bay of Bothnia in the Baltic Sea in March 2012.

The highest calculated peak load was 109 kN ± 17 kN with 95 % level of confidence. The analysis indicates that the uncertainty calculation can be applied to the global load calculation method. The uncertainty analysis is most sensitive to the changes in added mass and damping uncertainty. There are challenges related to the global load calculations from ship motions during impact with ridges or rubble fields so further study on the effect of the ship - ice interaction during these impacts is needed.

INTRODUCTION

Estimation of global ice load is important for designing ice-going ships and especially stationary floating off-shore structures in ice. Defining global loads from ship ice interactions is challenging and most often the load is estimated from the measured response.

Earlier a methodology to estimate ship global ice loads during impact events have been developed by National Research Council of Canada (NRC) (Johnston, 2006, Johnston, 2003, Johnston, 2005). They used a unit called MOTAN (MOTion ANalysis) to record ship motions in six degrees of freedom and the recorded values are turned to global forces using ships rigid body movements. System can handle both head on and oblique collisions. An application of the system has been on the global loads from impacts with bergy bits as described by Johnston (2004 and 2008a). According to Johnston (2008b) the system seems to give reasonable results compared to the results from local load measurement system at the point of impact.

AARI in Russia have used similar system in the estimation of the impact forces from the collisions with different ice features in the Barents Sea which was reported by Krupina (2009). There were two MOTAN units on board Kapitan Nikolaev. The ship was also equipped with another measurement system that measured general ship bending during the impacts with ice. Likhomanov (2009) reports the measurements and results analysis. Ten collision events were considered but the results show only relative loads due to the confidentiality. It was concluded that two independent measurement unit indicate similar load levels. The vertical global force estimated by MOTAN system gives 10 % lower force than force measured with the alternative system.

The results from the previous studies indicate that the methodology to estimate global load based on the inertial measurement system can give a good estimate for the global load for a single collision. The previous work gives a good basis to further develop and test the methodology to estimate global ice loading from ship motions.

There are many unresolved challenges with respect to ice itself and its interaction with the ship, which affect to reliability of the estimation of the calculated global ice load. Thus, some knowledge of the reliability of defined load levels is necessary, especially when defining ice loads for design purposes.

In this paper, a formal procedure to estimate the measurement uncertainty is demonstrated and tested for the global ice load calculation from measured ship motions. The challenges of the global load calculation and challenges related to the uncertainty analysis are discussed extensively.

MEASUREMENT SETUP AND DATA

The aim of the measurements was to record the ship’s global motions while impacting with different ice features such as ice ridges and large ice floes. A MRU of type Kongsberg/Seatex model MRU-H was used to measure ships motion with six degrees of freedom. The unit measures three linear accelerations and three angular velocities with three gyros. All other degrees of freedom of the linear and angular motions are derived from the measured parameters. The MRU was installed on a transverse bulkhead at the ship’s centerline close to the ship’s center of gravity. The system was recording continuously with 25 Hz frequency. Data was recorded in digital form in a central storage computer and afterwards used for global load analysis. Also the ships GPS data was recorded.

Data was recorded during the ice test cruise of SA Agulhas II in the Bay of Bothnia in the Baltic Sea in March 2012. SA Agulhas II is a 4780 DWT polar supply and research vessel build for South Africa by STX Rauma ship yard in Finland. Ice conditions during the cruise were mild for the time of the year.

The impact event used in the estimation of global ice load was a collision with a heavy rubble field where ship was transiting with 12 kn speed. The rubble field was an area of strong and thick ice that had been rafting and piling up over the course of several months forming a thick consolidated layer of strong ice. Even though air temperature was mild during the cruise this rubble field was heavily consolidated and forced the vessel to stop. The rubble field thickness varied a between from around 1.5 m up to 3.5 m being the thickest where the ship got stuck. Ship needed to ram two times to get through the heavy rubble field. This event caused much bigger drop in the ship speed than the ridge test in a profiled ridge that was formed from thinner ice and was less consolidated. It was also observed that there was some compression in the ice rubble field during the impact event from developing wind perpendicular to ships heading.

The ship decelerated from the cruising speed to full stop in just less than two minutes. The highest load peak occurred in the middle of the deceleration. For the design purposes the most interesting is the highest measured load so only one minutes time interval around the peak load was considered in the analysis of the global load.

Filtering measured data

Ship motion data recorded using the MRU includes data from a wide range of frequencies. Some of the higher frequencies are likely to come from other excitations than from the global ice load. The ship motion data was filtered to exclude these frequencies from the global ice load estimation. The filtering was made by using a so called brick-wall type low-pass filter. As a numerical filter it was easy to apply for the measured data in post-processing and allowed perfect cutting of high frequencies. In order to exclude high frequency disturbance from measurements, 5 Hz cut off frequency for all of the channels was used since ship motions are typically considered to occur at frequencies less than 5 Hz (Johnston et al. 2004 and 2008a). Filtering ship motion data has an effect to the estimated global load which is discussed later in this paper.

GLOBAL LOAD CALCULATION

In the calculation of the global load on the ship from the impact with ice the load is assumed to be a point load at the point of the impact. This example case it was assumed to be at the stem of the vessel. Global load can be calculated by solving ship's equation of motion in six degrees of freedom as presented e.g. Johnston et al. (2008b)

$$\{F\} = ([M] + [A])\{\ddot{x}\} + [B]\{\dot{x}\} + [C]x \qquad (1)$$

where *{F}* is the global force vector including linear forces and angular moments, *[M]* is the ships mass matrix, *[A]* is added mass matrix, *[B]* is the damping matrix and *[C]* stiffness matrix, *{x}* is the displacement vector and its first and second time derivatives are speed and acceleration, respectively.

When ship's surge, sway and heave linear movements and accelerations are considered together with pitch and yaw angular movements and accelerations the resultant global force at the stem of the vessel can be calculated

$$F_{res} = \sqrt{F_{surge}{}^2 + \left(F_{heave}{}^2 + \frac{M_{pitch}}{x_{bow}}\right)^2 + \left(F_{sway}{}^2 + \frac{M_{yaw}}{x_{bow}}\right)^2} \qquad (2)$$

where F_{surge} is the linear force in surge direction, F_{heave} is the linear force in heave direction, F_{sway} is the linear force in sway direction, M_{pitch} is the angular pitch momentum, M_{yaw} is the angular yaw momentum and x_{bow} is the distance of the MRU to the point of impact.

Ship's added mass, damping and restoring force matrices were calculated for calm open water condition using the Wasim software. Wasim is a nonlinear time domain hydrodynamic analysis software for fixed and floating vessels and it is part of DNV's Sesam™ HydroD software. Matrices are referred to the Wasim origin which in this case was set to be the location of the MRU to avoid moving the measured values from MRU location to other place using distance vectors. Matrices were defined for the speed range of the impact event. Ship's mass distribution, center of gravity and ship's floating position from the impact event were used as an input for the analysis.

UNCERTAINTY ANALYSIS

Uncertainty analysis of the methodology to define global ice load from measured ship rigid body motions was performed following an ISO guide (ISO, 2008), hereafter referred as "the ISO guide". Uncertainty is as defined by the ISO guide: "parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand". The measurand, in our case, is the global ice load. In the case of global ice load, the measurand is not measured directly but determined through the relationship of measured quantities through Eqs. 1 and 2.

The ISO guide divides the measured quantities into two categories. The first category includes quantities of which values and uncertainties are directly determined in the current measurement. The second category consists of the quantities of which values and uncertainties are brought into the measurement from external sources. The quantities in the case of the global ice load prediction procedure are likely to belong into the latter category. The ISO guide gives instructions on how to estimate the standard uncertainty of the parameters in this category. The standard uncertainty is defined by the ISO guide to be "uncertainty of the measurement expressed as a standard deviation". The ISO guide gives detailed instructions of the calculation of the combined standard uncertainty using definitions and examples.

The input quantities are first themselves defined by measurements of ship's six degree of freedom motions and measurements of the MRU location and derivation of the ship's mass matrix, added mass, damping and stiffness matrices. The standard uncertainties are then defined for all of the quantities based on the knowledge of measurement procedure and device. When defining the standard uncertainties e.g. for the ship motions knowledge on accuracy of the MRU provided by the manufacturer was used. Standard uncertainty for the input quantities was defined based on the knowledge of the error of the MRU and the GPS. For some of the parameters it was not possible to define the standard uncertainty. A good estimate of the standard uncertainty was missing e.g. for surge and sway position and hydrodynamic coefficients defined by the Wasim analysis. In such a case, the standard uncertainty was estimated using the best judgment available which might lead to some error in the estimation of the combined standard uncertainty. The sensitivity of the combined standard uncertainty to the changes in these parameters was tested to see the effect of the changes to the final result.

Once all standard uncertainties are defined the combined standard uncertainty (ISO, 2008) can be written as

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\cdot f}{\cdot x_i} \right)^2 u^2(x_i) \tag{3}$$

where $u_c(y)$ is the combined standard uncertainty and the right side of the equation is the sum the partial derivation of the mathematical equation *f* defining the measurand with respect to considered input quantity x_i squared times the value of the quantity's standard uncertainty $u(x_i)$ squared. The measurand and its combined standard uncertainty have the same unit. Sometimes it is necessary to define interval about the measurement result that covers a large fraction of the distribution of values. I that case the expanded uncertainty (ISO ,2008) can be used

$$U = ku_c(y) \tag{4}$$

where U is expanded uncertainty, $u_c(y)$ the combined standard uncertainty and k is the coverage factor. Finally the measured load and its uncertainty can be reported e.g. in the form of F_{res} kN ± U kN with 95 % level of confidence. The full description of the calculation method for the combined uncertainty and further details can be found in the ISO guide.

RESULTS

Ship motions were measured with the MRU. Of the considered one minute time frame the time around the maximum peak is the most interesting so all figures present a ten second time interval centered into the time of the peak load. Figure 1 shows the measured pitch and yaw accelerations and their filtered values with 5 Hz cut-off frequency. As can be seen a significant amount of high frequency data is filtered away. Especially in the yaw acceleration the peak of magnitude of 10 °/s^2 is much lower in the filtered data. The peak appears at the time of 54 second which is also the time for the largest calculated global ice load. This is likely to be the main source of difference between calculated load from the unfiltered and from the filtered motion data. Also the change in yaw angular velocity shown in Figure 2 at the same time indicates that heavier piece of ice hit the ship causing the load peak. There was major changes in yaw motion of the ship during the impact which indicates that the impact was rather oblique than a head-on collision.

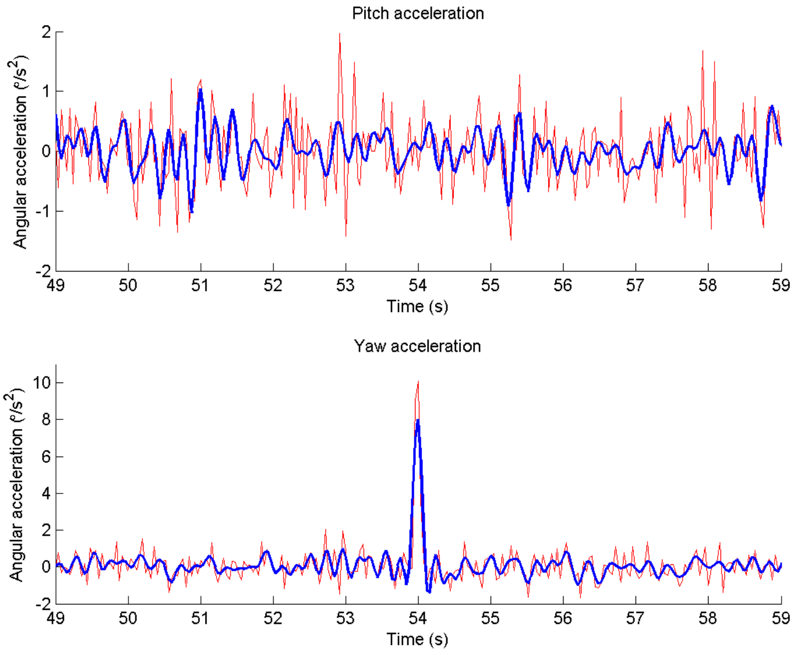

Figure 1 Measured pitch (above) and yaw accelerations (narrow red line) at the time of impact and the filtered values (blue thick line) with 5 Hz cut-off frequency.

The maximum global load from unfiltered motions was 140 kN where the maximum load from the filtered motions was 109 kN. Both loads are plotted in Figure 3. The load peak is rather short only around half of a second and its magnitude is relatively low. It is unlikely that this load peak alone was able to stop the ship, but rather the multiple contacts with ice and the compression in the rubble field were the cause of the stop.

The combined standard uncertainty for the global load was calculated based on the methodology from the ISO guide. The combined standard uncertainty for the peak load got a value of 8.2 kN. This yields to 8 % of relative uncertainty for the maximum load. The highest relative uncertainty was found at 58.6 seconds from the start of the impact event which is about four seconds after the peak load. At that point in time the combined standard uncertainty was nearly five times higher than the calculated global load. The load was 415 N and its combined standard uncertainty 2020 N. The global ice load and its uncertainty during the impact event are shown in Figure 4. For the lower loads the uncertainty is rather large compared to the loads at times even much larger than the calculated load.

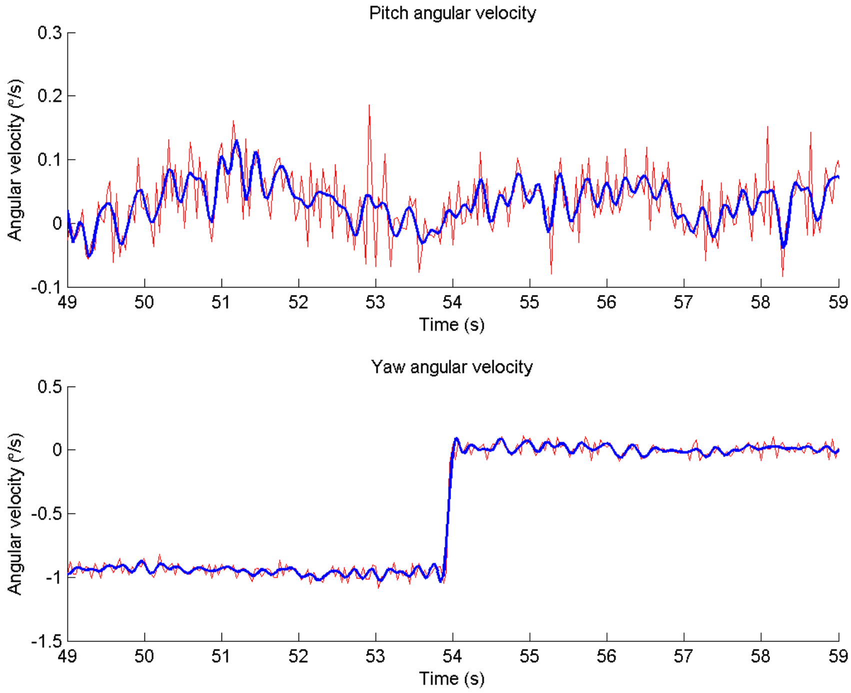

Figure 2 Measured (red thin line) and the filtered values (blue thick line) for the pitch (above) and yaw (below) angular motions.

The expanded uncertainty calculated with Eq. 4 was 17 kN. Therefore, the final result of the maximum load is reported to be 109 kN ± 17 kN with 95 % level of confidence assuming normal distribution for the measured value and its uncertainty.

The standard uncertainties for the sway velocity and displacement, surge displacement and ship mass, added mass, damping and restoring force matrices were assumed and thus it was clear that too conservative assumptions might lead to error in estimated combined standard uncertainty. Sensitivity of the combined standard uncertainty to the changes in standard uncertainties of these quantities was studied to see the effect of the assumed values to the final result. The results show that the combined standard uncertainty is not very sensitive to the changes of standard uncertainty of sway velocity or displacement or surge displacement. It is more sensitive to the change of the standard uncertainty in added mass, mass and damping matrices.

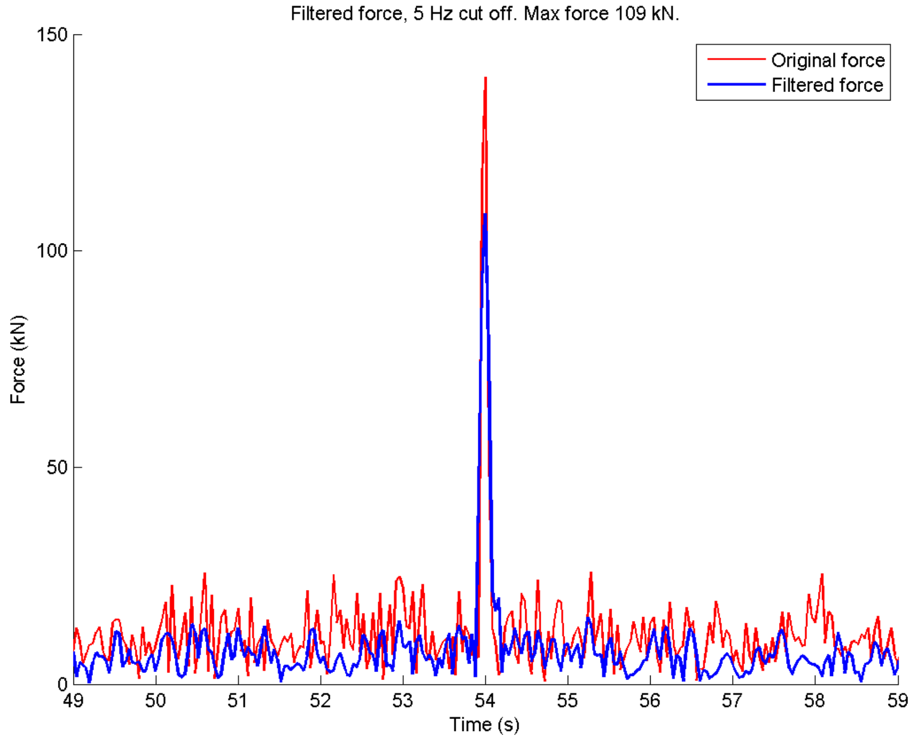

Figure 3 Calculated global ice force during impact with rubble field from unfiltered and filtered ship motion data.

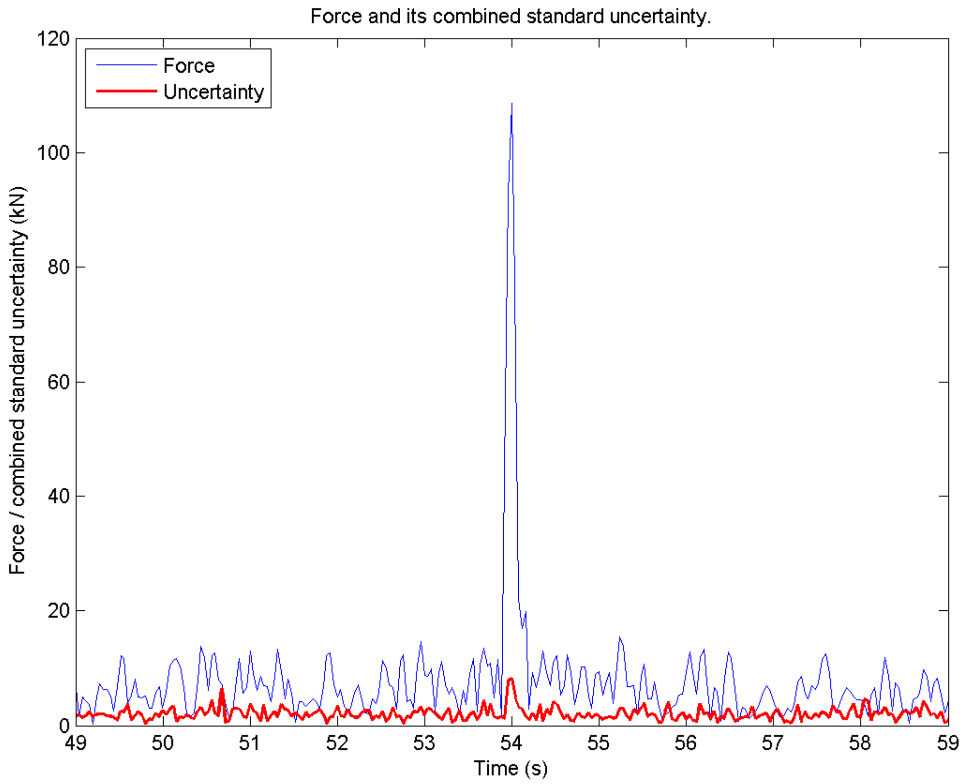

Figure 4 Calculated global ice force and it's uncertainty during the impact event.

DISCUSSION

The purpose of this study was to test how a formal uncertainty analysis is applicable for the ship global load calculation method. The study has shown that the uncertainty calculation methodology, being itself is a general method, is well applicable for this kind of problems. The studied impact event was not causing high loading on the hull. Regardless, the impact event was used to demonstrate the applicability of the uncertainty analysis for the global load calculation method.

Calculation of global ice load from the ship response challenging. Many parameters affecting to the final result are difficult to define for the case where ship is colliding with ice mass like ice ridges and rubble fields. Often it is considered that especially the ridges might cause the highest global loads and as such to be the design ice feature for offshore structures. Defining ship's added mass and damping coefficient in such a case where ship is in contact with multiple ice floes and when ice mass is also under the ship can be very challenging. Some times when observing an icebreaker ramming an ice ridge and getting stuck it looks like there is very high damping. This is evident especially in pitch motion when the ship rides in the ice mass. Damping and added mass coefficients defined for open water are not necessarily applicable for this kind of collision event. Use of them might ignore some of the features caused by ice surrounding the ship and lead to erroneous estimation of the global ice load.

The collision with a mass of ice floes does not necessarily cause a single peak load even though ship gets stuck in ice mass. There is likely to be more ice contacts along the hull causing the ship to stop. That is why it is very difficult to estimate the point of impact for the global load calculation. Observing the location of the point of impact is easier when ship rams a bergy bit in open water as done by Johnston et al. (2004) or a single ice floe in the sea area where ice concentration is low. In such a case also the open water damping and added mass coefficients suite better for the calculation and thus the global load can be more reliably estimated.

Everything mentioned above applies to the rubble field collision case in this study. Added mass and damping were defined for open water and the real point of impact is unknown. Calculated global load level is rather low compared to the ones reported by Johnston et al. (2008b). Generally, the calculated load level assuming the point of impact of being the stem were very low during the impact and only one peak higher appeared during the event. It is obvious that there had been lot of contacts along the ship hull and the assumption of stem as point of impact is not completely valid for the ramming a rubble field or an ice ridge. It should also be noted that observations on yaw motion of the ship during the impact indicate that the peak load was caused by an oblique collision with a heavier piece of ice in the rubble mass. This fact also makes the calculated the assumption of the point of impact being at the stem even more questionable.

One basic assumption in the global load calculation method is that ship hull is treated as a rigid body. It is thought that the recorded ship motions are caused by single force acting on the known location on the hull and that the hull is not deforming significantly due to the impact. This might be the case for icebreakers that have stiffer hull but not for commercial vessel having a more flexible hull. It was also observed on board SA Agulhas II that the bow part of the hull was flexible and clear motions could be felt by people at bow in waves. This undermines the basic assumption of rigid body motions in the load calculations. The fact that ship hull is flexible should be taken into account in the global load calculations especially when other type of ships than icebreakers are considered. It is not an easy task to estimate the flexibility, but because some energy is always dissipated in the elastic deformation, the calculated loads might be underestimated. One way of estimating the flexibility of the hull could be the use two or more MRUs in different locations of the hull and study the difference in motions and possibly implement them into the of finite element calculations to see how much the hull is deforming.

Filtering of the measured motions is problematic. The peak load dropped from 140 kN to 109 kN when all motion data is filtered using 5 Hz cut off for the low pass filter. It is likely that higher frequency motions are excited by other sources than ice impact. For example, the propeller blade frequency in the example case was filtered away. It would be advisable to take a closer look on motion data on each measured channel in frequency domain and decide the cut off frequency individually for each channel after careful consideration of possible source of motions in different frequencies.

Defining of the standard uncertainty for some of the input quantities such as sway and surge displacement was difficult. There was no necessary information available or the quantity measured by the MRU, for example, was considered to be inaccurate by the manufacturer. However, it is important to include the estimate of the inaccuracy of all input quantities into the calculation of combined standard uncertainty once the quantity is used in the calculation of the global load. Without better information on the error of the input quantity the standard uncertainty was estimated using the best judgment available. As was shown by the sensitivity analysis of the combined standard uncertainty calculation method, the combined standard uncertainty was most sensitive to the added mass uncertainty and secondly mass uncertainty. Thus the estimated standard uncertainties even selected to be conservative did not have great effect on the combined standard uncertainty in this example case. Further study on defining the standard uncertainties of input quantities is needed in order to define them more reliably.

It is recommended that when performing measurements related to the arctic technology some estimate of the uncertainty of the results is reported to get understanding of the validity of the measurements. Uncertainties related to ice measurement are likely to be large. Therefore, it is important that the one doing the measurement has gone through some formal procedure to estimate the uncertainty and its sources in order to be able to reduce the uncertainty and communicate it to scientific community together with the measurement results.

CONCLUSIONS

This paper has shown an example of the uncertainty analysis applied to ship global load calculation and discussed the challenges related to the load and uncertainty calculations. The formal uncertainty analysis is applicable to the global load calculation methodology. It was noted that some challenges in both global load and its uncertainty calculations remain and further study address these challenges is needed.

Calculated uncertainty for the peak load is relatively low level only 8 % of the peak load indicating that the calculated load was relatively well describing the real load. The calculated peak load level is significantly smaller than reported in bergy bit impact studies.

The global load calculation methodology needs more development if the calculated loads are planned to be used in design purposes especially when it comes to the assumptions on the point of impact and ship hull rigidity.

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