POAC'13
Espoo, Finland

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

EVALUATION OF GLOBAL ICE LOAD IMPACTS BASED ON REAL-TIME MONITORING OF SHIP MOTIONS

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ABSTRACT

As part of the ColdTech program, the Norwegian Coastguard vessel KV Svalbard has been equipped with an inertial measurement device (MRU) to record global ship motions in six degrees of freedom during ramming of heavy ice features. The objective of the measurement campaign was to look further into the possibility of using recorded whole-ship motions to evaluate the response of the ship and the global loads acting on the hull for different types of ship-ice interactions. The system has been tested during two expeditions around the Svalbard islands and the Fram Strait in 2011 and 2012.

This paper should be considered as an introduction to the measurement campaign, and discusses the authors' views on the applicability and limitations of such a monitoring system. Although similar measurements have been carried out in earlier projects, the actual usability of the system and the potential for further development to obtain a better understanding of the ice loads and the ship response during ramming have not previously been discussed in detail. The post-processing of the recorded data and further evaluation of the global ice loads derived from the measured ship motions are discussed in brief and exemplified using the recordings from a controlled impact with a distinct ice feature. Detailed discussions and validity of results will however be presented in a separate paper. Assumptions made and uncertainties connected to the proposed procedure are also discussed.

INTRODUCTION

Ships operating in polar and cold climate conditions may experience extreme loads and impacts from heavy ice floes as well as floating and drifting icebergs. Such impacts, which may or may not be intentional, can be of both static and dynamic nature, and appropriate dimensioning methods are needed in order to provide sufficient structural integrity and safety, and limit damages of ships.

Ice loads are among the most uncertain of all loads applied to ships, and it is hardly possible to link any design loads for an actual trading vessel to a formal probability level or return period. Hence the probability of unintentionally encountering ice loads which exceed the limits to which the vessel is built may be significant, mainly due to the difficulties related to evaluating the actual ice conditions, and correspondingly the severity of an ice impact.

Full scale measurements of ice-going ships have for many decades played an important role in the understanding of the processes involved in ship-ice interactions. Measurements of both local and global ice loads have probably been one of the most important factors in formulating and deriving governing design and rule formulations for ships operating in ice covered waters.

Still, there is a common opinion within the industry that the lack of high-quality data is one of the most important factors limiting the further understanding of ship-ice interactions.

As part of the Ice Load Monitoring (ILM) project and later the Coldtech project, DNV has had the opportunity to use the Norwegian Coastguard vessel KV Svalbard as a platform for extensive full scale measurement programs. In 2006, the ILM project (Mejlænder-Larsen & Nyseth, 2007) was initiated with the objective of developing tools which could be used to provide additional information of the actual ice conditions and the corresponding ice loads acting on the hull structure. Different systems providing various types of information, including an extensive instrumentation of the bow structure, were integrated into a single source of information to act as a decision support system for safe and effective operation in ice covered waters. The initial measurements focused mainly on local ice loads in the bow area, but the system was in 2010 extended to include global loads and response by the use of an inertial measurement device called MRU (Kongsberg Seatex AS, 2006).

Increased knowledge of the global loads acting on structures is important for many applications. Typical examples are given below:

- Design loads for ships and offshore structures (Ultimate Limit State design)
    - Fixed offshore structures
    - Primary strength members in the forward area of the ship
    - Ship hull girder strength
- Unintentional impact loads (Accidental Limit State design)
    - Unintentional impact with heavy ice features and icebergs
- Global accelerations
    - Fastening of equipment
    - Design accelerations for cargo loads
    - Sloshing
    - Human safety

The measurement campaign is a part of the ColdTech project, which is a Norwegian research program aimed at developing a knowledge and competence centre in Northern Norway within the fields of Arctic Engineering. The objective of the current measurement campaign is to obtain full scale data to evaluate some of the abovementioned aspects. The measurements also fit into other research tasks within the ColdTech project, where the objective is to gather statistical information about the structural geometry and properties of first year ice ridges, which further will be used as basis for the development of numerical models of the ice. The intention in the long run is to see if these types of full scale measurements also can be used to calibrate numerical models of ice ridges.

INERTIAL MEASUREMENT SYSTEMS FOR EVALAUTION OF GLOBAL ICE LOADS

Background

Global ice impact loads have traditionally been measured by the use of strain gauges. During the late 70’s and 80’s, full scale ramming tests were carried out on several icebreakers and cargo ships, which among others were used to derive and calibrate design requirements given in various rule formats, e.g. for the DNV Polar and Icebreaker notations (DNV Rules for Classification of Ships, 2013). The first attempts to determine global ice loads from full-scale measurements of the global motions of the ship were made by Canadian Hydraulics Centre (CHC). In April 2000, the USCGC Healy was instrumented with an inertial measurement system called MOTAN which based on rigid body motion recordings determines external ice forces due to an impact with heavy ice features. Following the Healy trials, the MOTAN system has been installed on several icebreakers and commercial vessels (Johnston et.al, 2001,2003, 2005).

In 2008 the Arctic and Antarctic Research Institute (AARI) (Krupina, N,et al., 2009, and Likhomanov, V. et. al, 2009) carried out similar experiments with the Russian icebreaker Kapitan Nikolaev as part of the expedition “Shtockman 2008”.

In both cases, impacts from various ice features were evaluated, including bergy bits and hummocked or ridged ice fields. The resulting global forces were in general estimated based on the general equation of motion, which may be given on the following format:

$$\{F\} = [M + A]\{\ddot{\eta}\} + [B]\{\dot{\eta}\} + [C]\{\eta\} \tag{1}$$

where **F** is the external forces acting on the vessel, M, A, B, and C are the mass, added mass, damping, and restoring coefficients, respectively, and η (and its derivatives) are the recorded ship displacements, velocities and accelerations.

As long as the hydrodynamic coefficients (and any other external forces if relevant) are known, the ice impact load may be determined based on the recorded accelerations, velocities and displacements in the six degrees of freedom, provided that the location of the impact is known.

Description of the Motion Reference Unit (MRU)

KV Svalbard is equipped with a Motion Reference Unit (MRU-H) which is considered similar to the devices used for the previous measurements described above. The unit measures the rigid body ship motions in all degrees of freedom, namely:

- Linear translations in three perpendicular axis directions
- Rotation about three perpendicular axes

The MRU is produced by Kongsberg Seatex AS, and is shown in Figure 1. The MRU axis system is shown below, where the *F* axis points forward, the *S* axis points starboard, and the *D* axis down. Rotational motions are positive counterclockwise.

Physical dimensions:
Height: 204 mm
Diameter: 105 mm
Weight: 2.5 kg

Output variables from MRU:

	Surge	Sway	heave	Roll	pitch	Yaw
Acceleration	X	X	X		X	X
Velocity	X	X	X	X	X	X
Displacement	X	X	X		X	X

Figure 1. MRU configuration

The MRU consists of three accelerators measuring the accelerations in surge, sway and heave, and three angular rate sensors measuring the velocities in roll, pitch, and yaw. The remaining 12 variables are calculated either as the derivatives from the angular velocities or by integrating the accelerations and/or velocities. The recorded and calculated ship motions are stored with a time stamp in binary format in a central measurement unit, which also feeds the MRU with heading, velocity data and power. The signals were generally recorded with a sampling rate of 25 Hz.

It should be mentioned that the MRU has a limit of 16 output variables, meaning that two out of the 18 available variables must be excluded from the output list. For the KV Svalbard measurements, the roll displacement and acceleration were removed, as those were assumed to have the least impact on calculated impact loads. These variables may however be manually estimated based on the recorded roll velocity.

System potential, applicability and limitations for estimation of global loads

An inertial measurement system has several advantages compared with a strain gage based system. The most obvious advantage concerns the preparations and installations, for which a gauging system easily can be a time consuming and costly process, as well as maintenance and reusability of the system. An inertial measurement system can basically be designed as a “stand-alone” system which easily can be mounted/demounted and reused on other ships when needed.

To ensure confidence and reliability of full scale measurements, data should be received from independent measurement systems. Hence, development of measurement methods which can be used as supplement to other well established methods such as strain gauging etc. are important.

There are however several factors which potentially affect the accuracy of the results and put limitations on the use of the inertial measurement system, both with regard to post-processing of data and the subsequent calculation of impact loads. The first aspect relates to the post-processing of recorded signals, and to ensure that this is being done with sufficient degree of confidence and accuracy. This includes the three accelerators and three angular rate sensors which are used to determine the 18 parameters describing the ship accelerations, velocities and displacements in the six degrees of freedom (surge, sway, heave, roll, pitch and yaw) .Uncertainties are related to among others sampling frequencies, filtering techniques, and the estimation of the twelve remaining output variables which are not explicitly measured. Particularly there could be uncertainties related to the motions in the horizontal plane, i.e. the surge, sway and yaw motions. It has to be ensured that these motions are purely dynamic, and that no unintentional drift in the data signals is found.

The estimation of impact loads based on the general equation of motions (Eq. 1) requires information about all external forces acting on the ship. In addition to the added mass, the damping and the restoring forces which explicitly are included in the equation, the effect of a potential (relative) change in thrust and remaining hydrodynamic and other ice-related forces acting on the hull have to be considered. This could be of some importance particularly for impacts resulting in a significant drop in velocity, or when impacting a feature which is embedded in an ice floe.

The ship is considered to behave as a rigid body which means that no elastic deformations along the hull girder are assumed. This assumption may be reasonable for a smaller icebreaker such as KV Svalbard, but can certainly be questioned for a larger tanker or similar.

Based on the experience so far, the system is found promising for evaluating impact forces acting on the ship. There are however particularly two aspects which potentially could put some limitations to the use and further applicability of the system, namely:

1. **Selection of impact scenarios** - the current use is generally limited to the case where the ship is impacting a heavy ice feature (growler or ice edge) from calm open water.
2. **Automation of system –** identification of an impact from the data signals alone is found difficult, which means that additional information is needed in cases where manual logging is not an option, in order to identify the real impacts of interest.

The main challenge is to distinguish the ship response being a direct result of the bow impact (for which the impact location is known) from the random motions the ship may experience due to ice interaction along the hull when operating in an ice field. In order to estimate impact forces based on recorded motions, the response from the single bow impact force must be isolated. No proven methods have so far been able to do so. Hence, this means that the system is not reliable for assessing impacts of e.g. an ice ridge embedded in ice. Even when impacting an ice edge from open water, the procedure is only valid for a few seconds after the initial impact, as the response gradually will be affected by other forces and impacts along the hull when proceeding further into the ice.

CASE STUDY

In the following, the procedure for post-processing of data signals and further calculating the ice impact loads is briefly described using the data obtained from one specific impact recorded on the second ColdTech expedition with KV Svalbard. Detailed discussions and validation of the results will be presented in a separate publication, and will hence not be discussed in detail here. The expedition took place in the Fram Strait in March 2012, see Figure 2. The vessel left Longyearbyen 9th of March heading northwest towards the northern parts of Greenland. When well set into the ice, the vessel followed the ice drift for six days before heading back to Svalbard and Longyearbyen. The location of the impact case discussed in the following is indicated with a circle below.

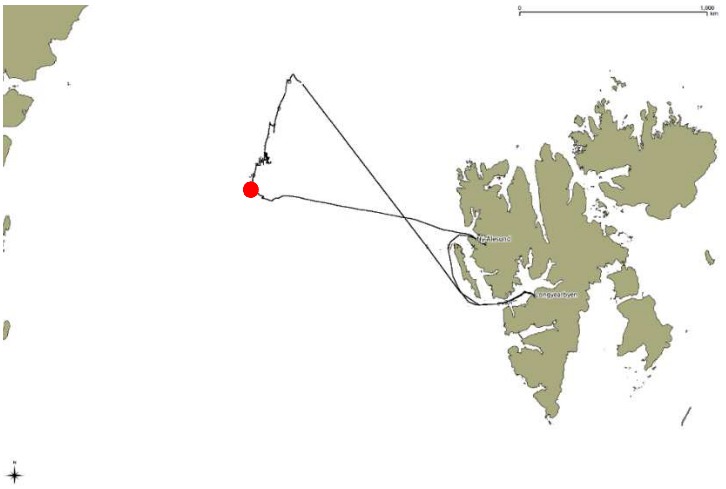


Figure 2. Actual route of KV Svalbard during the 2012 Coldtech expedition

The vessel

The Norwegian Coastguard icebreaker and patrol vessel *KV Svalbard* is built at Langsten Slip & Båtbyggeri and put into service in January 2002. The vessel is homeported in Sortland and has the Arctic waters north of the Norwegian mainland, the Barents Sea and the areas around the Svalbard islands as her primary operating areas. Her main duties include enforcement of sovereignty, fishery inspection, search and rescue, environmental protection and other support tasks, as well as various types of research activities.

The main vessel particulars are listed in Table 1.

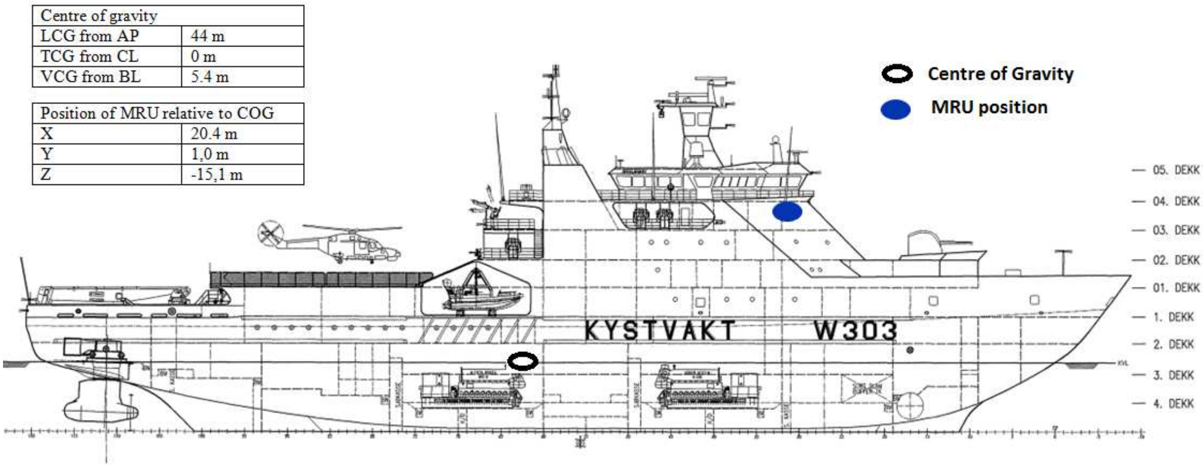
Table 1. Vessel particulars

Loa	103.7 m
Lpp	89.0 m
B	19.1 m
D	8.3 m
T	6.5 m
Displacement	6530 t

The vessel is assigned the DNV ice class notation POLAR-10 Icebreaker, and is designed to operate in first-year and moderate multi-year ice conditions.

MRU location

The MRU is mounted on the longitudinal bulkhead at frame #29 close to the centre line of the ship in the server room at 03 deck. The position of the MRU relative to the centre of gravity (MRU coordinate system) is given in Figure 3.



Centre of gravity	
LCG from AP	44 m
TCG from CL	0 m
VCG from BL	5.4 m

Position of MRU relative to COG	
X	20.4 m
Y	1,0 m
Z	-15,1 m

Figure 3. Location of MRU

Considered impact event

The impact was recorded on 16 March at 09:23:07 UTC, as the vessel impacted a distinct ice edge with a thickness of more than 2 m from open water. The calm open water condition prior to the impact made it possible to isolate the ship motions due to the ice impact.

In principle, the ice impact evaluation consists of the following steps:

1. Event identification
2. Define time of impact and duration
3. Filtering and calibration of time signals
4. Isolation of ship motions exclusively caused by the ice impact in the bow
5. Calculation of impact forces

For the considered impact, the processed surge, heave and pitch accelerations at the MRU position are plotted in Figure 4 where the vertical lines are defining the defined impact duration.

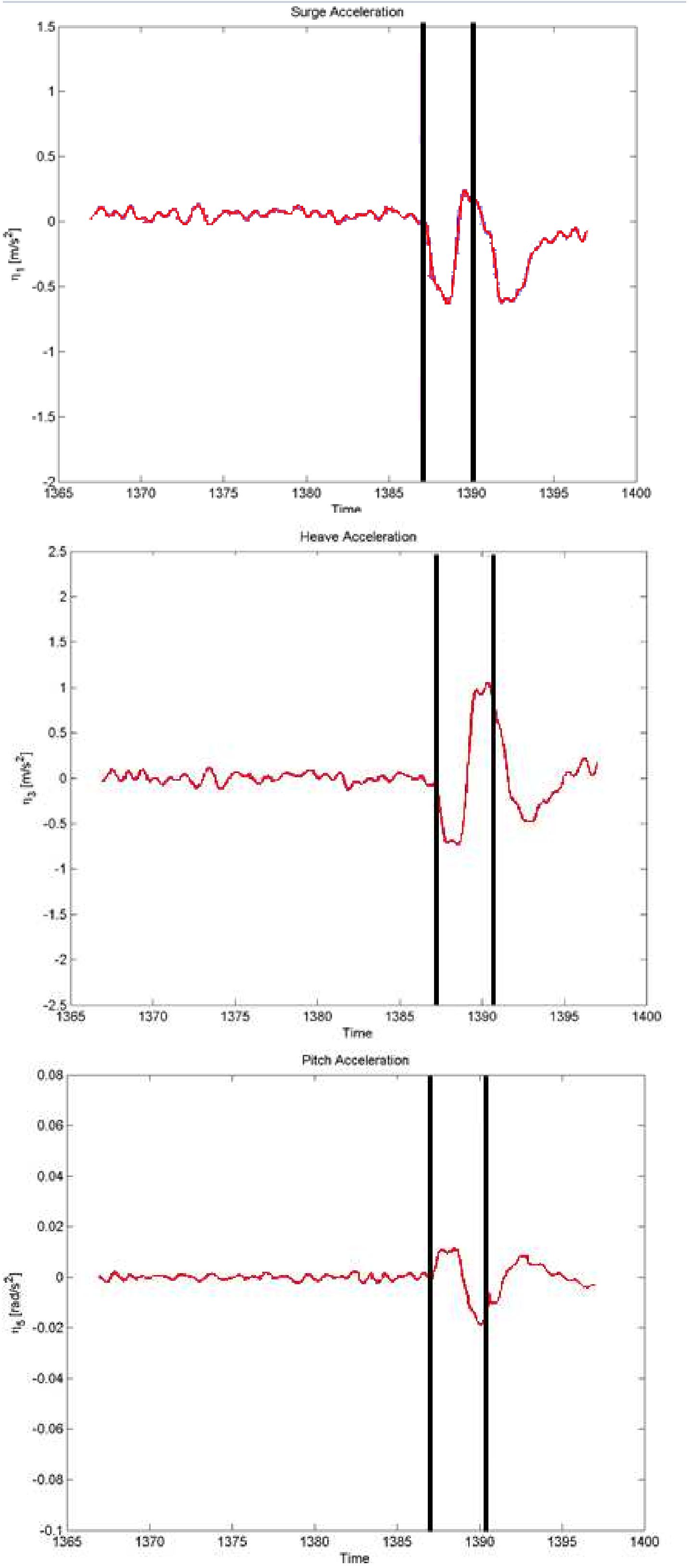


Figure 4. Filtered signal for the surge (upper), heave (middle) and pitch (lower) acceleration components. The vertical lines indicate the impact duration.

For each impact, the time of impact and the impact duration have to be defined. For the current impact, the duration is taken as approximately three seconds from the time of the first impact. The time of the first impact is defined as the first cross over point (the point where the measured motion crosses zero) before the first time response exceeds 25% of the maximum value within the considered interval. After the defined interval duration, the bow is assumed to have ploughed deeper into the ice masses, and the recorded responses are believed to be gradually influenced by other factors than the initial ice impact, which means that the calculation method used is no longer valid.

The filtered signals are based on the recorded raw signals where the signal noise and oscillations not considered being a result of the impact are removed using different filtering techniques. In Figure 5 the heave acceleration is plotted in frequency domain.

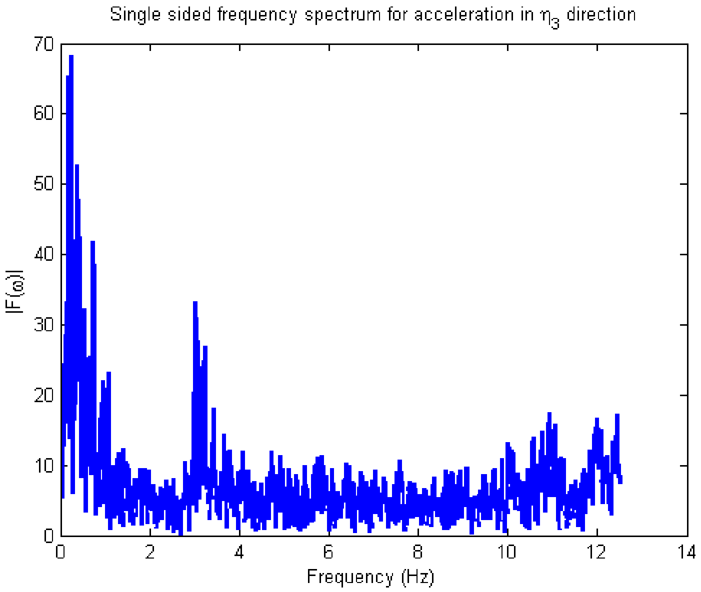


Figure 5. Heave accelerations during impact in frequency domain

For the heave component, it is seen that there is a major response component around 3 Hz, which coincides well with the 2-node frequency mode of the vessel. Hence, it was decided to filter the frequencies above 2Hz. The same evaluation is done for the other degrees of freedom. In addition, response components which are found to be a result of noise in the measurement system are identified from calm open water condition and removed separately. As mentioned above the remaining response variables are automatically integrated or derivated by the MRU. However the integrated signals or the derivatives have to be manually controlled to ensure that no artificial or unintended responses are present.

Brief description of the estimation of impact loads

The impact loads will generally be calculated based on a procedure which is similar to those developed for the MOTAN system discussed above, where the individual force components are calculated based on the general equation of motions. The calculation procedure will however not be discussed in this paper.

In the current assessment, the hydrodynamic (added mass, damping and restoring) coefficients have been determined for a certain speed range using the hydrodynamic program WASIM. The code was slightly modified to take into account the presence of ice in front of the ship. The ice is generally modelled as horizontal “thin walls”, forcing the wave elevation below the ice to be zero and the fluid velocities just below the ice to be horizontal. The method for calculating the hydrodynamic coefficients in ice will be presented in a separate paper, and the uncertainties and influence of the coefficients are discussed in (Valkonen, 2013).

As mentioned above, this paper will not discuss the results from the measurements, but an example of the calculated impact force is given in Figure 7. The calculated force is plotted from the defined time of contact including the following three seconds. The results after the defined impact duration is shaded, as the response is no longer assumed to be a direct result of the impact, and the calculation procedure is hence not considered valid.

The ship responses and the calculated reaction forces obtained from the general equation of motion will be compared and validated against other measurements and more analytical procedures, e.g. an evaluation of the integrated impulse load based on the change in momentum during the impact. The advantage of using the principles of conservation of momentum to determine the impact forces is that only the velocity components need to be considered.

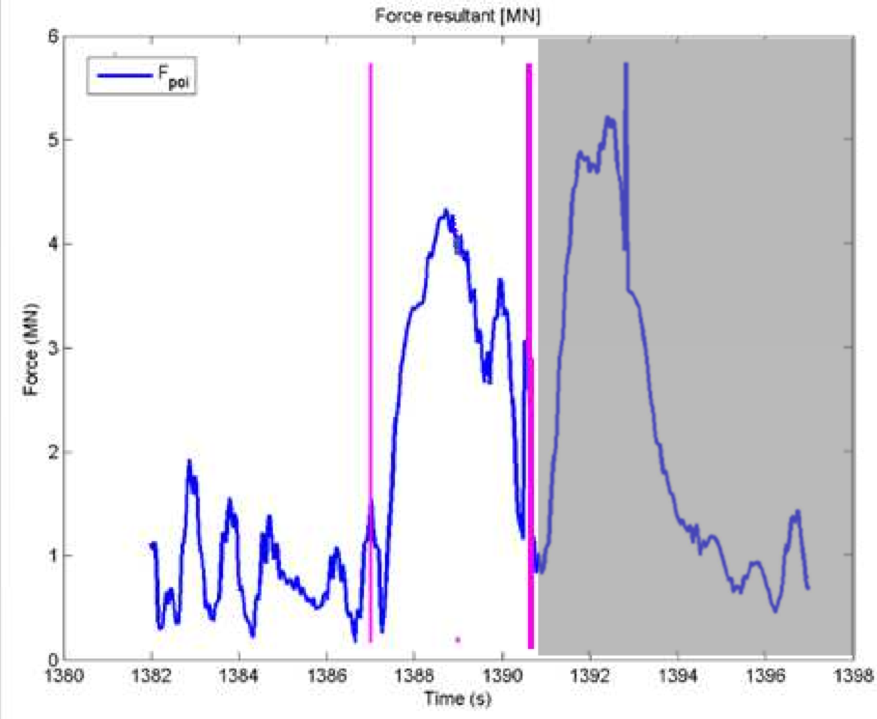


Figure 7. Illustration of calculated resultant impact force plotted from the defined time of contact

CONCLUSION

This paper is to be considered as a background document and discusses the recent experience gained through the installation of an inertial measurement system onboard the Norwegian icebreaker KV Svalbard. The objective of the measurement campaign was to further develop methods for evaluating the global ice loads acting on the ship when impacting a heavy ice feature. The system seems to have potential for cases where the ship is impacting a heavy ice feature such as an ice edge or a bergy bit from open water, but more work has to be done to develop methods which are applicable for general impacts in an ice field, including automated systems which can provide reliable data in different ice conditions and potentially being part of an integrated decision support system. A detailed documentation of results obtained from the measurements will be presented in subsequent papers.

ACKNOWLEGEMENTS

The authors will like to acknowledge the Norwegian coastguard and KV Svalbard, represented by the captains Roar Lund and Charles Blålid. Their hospitality and support during the voyages have been highly appreciated. In addition, we would like to thank the other partners in Coldtech.

Mathias Broman and Per Nordquist have post-processed the data as part of their Master Thesis at Chalmers University of Technology in Gothenburg. Their work has been highly appreciated.

This work was supported by Norwegian Research Council project number 195153.

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