Estimation of Forces caused by Ship-Ice Interaction using on-board Sensor Measurements

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ABSTRACT

The main objective of this paper is to describe a method to estimate severity of the forces caused by ship-ice interaction using only sensors regularly available on a position-moored vessel. Commonly available sensors are contained in an inertial navigation system (INS), consisting of a position reference system (GNSS), a heading reference system (e.g. a gyrocompass) and an inertial measurement unit (IMU). The data recorded by these sensors contains information about the ship-ice interaction, which can be extracted using suitable filter techniques. This paper will give an overview of existing filter techniques, which can be applied for spectral analysis of ice-load measurements. Furthermore, first results from a ship-ice interaction simulator will be presented which verify the usability of INS sensor data for ice load identification.

Abbreviations

- $f$: Frequency
- GNSS: Global navigation satellite system
- GPS: Global positioning system
- IMU: Inertial measurement unit
- INS: Inertial navigation system
- $L_S$: Total power of a signal $S$
- PSD: Power spectral density
- $\varphi_{ss}(\tau)$: Autocorrelation function of signal $S$
- $\phi_{ss}(f)$: Fourier transformed autocorrelation function
- $\mathcal{E}\{S\}$: Mean value of signal $S$
- $\mathcal{F}(S)$: Fourier transformation of signal $S$

Introduction

Position moored objects such as ships or buoys are affected in open sea by incoming environmental forces such as ocean current, wind and waves. If a position moored vessel operates in an ice infested environment such as the Arctic, the forces caused by ship-ice interaction will most likely become dominant, as it has been observed for fixed structures (Yue et al., 2007). Especially if additional stiffness is provided to the mooring, for example by means of thruster assistance, it will be crucial to get information about the ice-induced forces acting on the stationkeeping vessel (Nguyen et al., 2011). This paper presents a way of obtaining information by utilizing the sensors that are normally present on-board a sea vessel. With
suitable signal processing techniques, it is possible to use the sensor readings for ice load estimation. The information about the attacking forces caused by the sea-ice can be used to autonomously decide on an ice management strategy for protection of the position-moored vessel. This paper is a first description of the idea of using ship sensors for ice load estimation and does not yet provide a full operational scheme for ice load estimation.

The paper is divided into five parts. The first part of this paper is a review on literature about different ice loads on structures. During the second part the available sensors on-board a position-moored vessel are introduced. Suitable signal processing techniques for analysis of the measured signals are presented in the third part of this paper. A simulation of ship-ice interaction has been conducted and the results are presented in the fourth part of this paper. The last section of the paper will conclude the idea of sensor based ice load detection by suggesting further experiments.

**Ice loads on structures**

Yue et al observed that ice failure modes have characteristic force patterns which occur during structure-ice interaction (Yue et al., 2009). The force pattern depend on the natural frequencies of the structure, the form of the impact area, the energy delivered by the ice onto the structure and further environmental conditions such as wind. Yue et al. (2009) differentiate the ice force patterns in three categories:

- Quasi static ice force (a)
- Locked-in ice force (b)
- Irregular ice force (c)

Examples for three different ice force patterns for a monopod structure are shown in Figure 1.

![Figure 1: Different ice force patterns and corresponding displacement measurements (Yue et al., 2009)](image)

The occurrence of the ice force patterns depend on the failure mode of the ice and the natural frequency of the structure. In case of a ductile failure of the ice (which for example occurs during bending and cracking), a quasi-static ice force pattern can be observed. The ice force increases slowly until a critical limit has been reached and the ice fails which results in a sudden drop of force. The ice undergoes a considerable plastic deformation and few cracks can be observed (Yue et al., 2009). In Figure 1 a) a hull frequency can be observed. If the frequency hits the natural frequency of one of the degrees of freedom of the structure, the ice force becomes locked-in the natural frequency. Damping will be limited and thus the oscillation will be sustained. The resulting oscillation is globally measurable on the structure (Yue et al., 2009).

If the ice forces reaches a certain limit, the failure of the ice will behave in a brittle manner. The resulting forces acting on the structure are of chaotic nature, inducing random vibrations into
the structure or ship as shown in Figure 1 c). Similar results can be found in (Kärnä and Jochmann, 2003, Sodhi and Morris, 1986). The failure mode depends significantly on the energy the ice can induce into the structure. The available energy during impact is related to the velocity of the ice (kinetic energy) and the mass of the ice (potential energy), which again is related with the thickness (Timco and Weeks, 2010, Wright, 2000) and, in case of ice ridges, the porosity of the ice (Strub-Klein and Sudom, 2012). A relation between ice thickness and ductile or brittle failure is given in (Kärnä and Jochmann, 2003) and illustrated in Figure 2.

![Figure 2: Correlation between ice thickness and failure mode (Kärnä and Jochmann, 2003)](image)

The transition between ductile and brittle failure can be abrupt as described in (Bjerkås et al., 2007). Brittle crushing is responsible for inducing high frequency oscillation into the structure, which can be monitored by acceleration sensors throughout the ship. Figure 3.3 shows an acceleration measurement during the transition between ductile and brittle crushing.

![Figure 3: Ice load showing sudden brittle crushing and corresponding acceleration measurements (Bjerkås et al., 2007)](image)

The measurements of Bjerkås where conducted at the Swedish Norströmsgrund lighthouse in the Baltic Sea. The acceleration measurements indicate a huge energy transfer into the structure caused by the structure-ice interaction. It will be necessary to estimate the power acting in these moments. Since observations of this behaviours are available mostly for fixed structures, it will be important to evaluate the threat caused by ice action on stationkeeping ships. The severity of the ship-ice interaction depends on the accelerations caused by the ice load. The next chapter will therefore describe sensors that can be utilised on-board a vessel to measure the accelerations caused by ice loads.
Sensor Technologies on-board a position mooring vessel

Three major sensor technologies will be considered: Inertial measurement units (IMUs), Satellite based movement tracking and direct hull force measurements. This chapter will give an overview of how these sensor technologies can be integrated in order to achieve higher precision and redundancy.

Inertial measurement unit (IMU)

An IMU is an assembly of up to seven independent sensors, combined with an intelligent hardware for the merging and calibration of the measurements. The assembly of sensors consists of three gyro-meters, measuring the angular velocity in pitch, roll and yaw. The accelerometers measure the linear accelerations in surge, sway and heave. Altogether all six degrees of freedom for a marine structure or vessel are been measured. In order to obtain the actual linear position, it is necessary to integrate the linear accelerometer signal twice. In order to obtain the actual angle in each degree of freedom, it is necessary to integrate the angular velocity signal once. Each measurement is accompanied by errors. The errors can be caused by misalignments, temperature variations or sensor biases. It is necessary to obtain further position information to correct for this drift in the measurements. Johnston et al. (2004) used IMU measurements to evaluate the forces acting on a ship during impact with glacial ice. They presented good first results for roll acceleration but still further development is necessary in order to obtain pitch- and yaw accelerations correctly.

Inertial navigation system (INS)

To obtain a precise position and attitude information, the measurements obtained from the on-board IMU system and an external global navigation satellite system (GNSS) can be combined. The overall system containing the IMU, the GNSS receiver and a software for combining the measurements is referred to as inertial navigation system (INS). The software consists of a noise reduction filter such as a Kalman filter, that eliminates white noise error from GNSS measurements and an integration filter that compares the measurements of the IMU system and the GNSS and removes acceleration and gyro biases by feedback. A detailed description of the filters and overall system can be found in (Fossen, 2011).

Figure 4: Concept of measurements combination of IMU and GNSS

Hull panel sensors and hull vibration measurements

Besides the already installed IMU and GNSS sensors, it could be possible to add further sensor technologies in order to achieve a higher precession. Yue et al. (2009) mounted load panels directly on the ice load affected parts of the structure’s hull. This allows a direct measurement of the occurring forces at the cost of additional sensors that have to be installed and are not part of standard sensor equipment on an ocean vessel or structure. For academic testing however load panels can provide a reference signal of the ice loads to allow a comparison of measured signals by the INS. A similar concept is followed by hull strain measurement such as presented by Leira and Børsheim (2008). Strain measurements at internal support structures involves less complicated modification to the vessel than the installation of load panels.
A further option is to measure the local hull vibrations induced by the ship-ice interaction. The hull vibration are similar to the measured accelerations by the IMU but if the measurements are taken directly at the hull by means of vibration sensors or acoustic sensors such as microphones, the precession will be much higher. However, additional sensors and installations will be necessary. Ice load or wave caused vibration measurements have been conducted and described by Ramos and Soares (1998) and Amdahl et al. (2009).

**Frequency domain analysis**

The amount of power induced in the ship is relevant to evaluate the severity of ice-ship interaction. Therefore, it makes sense to evaluate the power density spectrum of the measured acceleration signals.

**Power density spectrum**

The power density spectrum decomposes a power signal into infinitesimal small portions of the frequency band. For each frequency the power contribution to the overall power of the signal is shown. *Parseval’s theorem* states that the integral over all frequency results in the total power of the signal.

\[
L_s = \int_{-\infty}^{\infty} \phi_{ss}(f) \, df
\]  

(1)

The power density spectrum can be calculated by utilising the *Wiener-Chintschin theorem* (Ohm, 2012). It states that the power density spectrum can be fully evaluated by applying the Fourier-transformation on the autocorrelation function of the measured signal.

\[
\phi_{ss}(f) = F(\varphi_{ss}(\tau))
\]  

(2)

Figure 5 shows the power spectra of two crushing tests of a rigid cylindrical structure against a sheet of ice. The left plot shows the power density spectrum of a test conducted at low-velocity. The right plot shows again a power density spectrum, but this time test has been conducted at a higher velocity. It is obvious that if the integral is taken over all frequency, the overall power for the test of low velocity is smaller than for the higher velocity test. Besides that obvious observation, each test shows a significant peak of relative power for a characteristic frequency. In the case of low power this peak is observable at around 3 Hz, while this peak is shifted for the higher velocity test to around 8 Hz. The exact test configuration and force signals can be found in (Sodhi and Morris, 1986). During brittle crushing however a huge variety of frequencies act due to the chaotic patterns of the signal. To overcome this problem Kärnä et al. (2004) proposed the use of autocorrelation functions for signals of stochastic nature.

![Figure 5: Power density spectrum of two ice-structure interaction tests with different velocities (left: low velocity, right: high velocity) (Sodhi and Morris, 1986)](image)
**Autocorrelation function**

Before the autocorrelation function can be calculated, it is necessary to differentiate stationary from non-stationary processes that cause a signal $s(t)$. Kärnä et al. (2004) claim that ice actions can be described as stationary process. They analysed the ice-action on a lighthouse in the Baltic Sea and in their case the assumption of stationarity works. Also Bjerkås et al. (2007) observed stationarity for ice load signals but states, that there are also non-stationary effects governing the ice crushing dynamics. Therefore, it is not yet proven, that all ice actions can be described by stationary processes. It is interesting to investigate, weather the load signals can be regarded as wide-sense stationary, which would allow the usage of stationary signal analysis. In case of a stationary or wide-sense stationary process, the autocorrelation can be evaluate as a time average.

$$\varphi_{ss}(\tau) = E\{s(t) \cdot s(t+\tau)\}$$  \hspace{1cm} (3)

There are two important properties of the autocorrelation function. First, the autocorrelation function is even, meaning $\varphi_{ss}(\tau) = \varphi_{ss}(-\tau)$. Second, the maximum of the autocorrelation function is at $\tau = 0$ and applying Parseval’s theorem (1) gives the instantaneous overall power the signal $s(t)$.

$$L_s = \varphi_{ss}(0) \leq |\varphi_{ss}(\tau)|$$  \hspace{1cm} (4)

**Simulation of ship-ice interaction**

A simulation of a floating structure towed through a user configurable ice field has been conducted. The idea is to evaluate the usability of acceleration data for ice interaction estimation and to test spectral analysis method such as the power spectral density. The structure was towed at different velocities through an ice field with randomly sized ice floes of equal thickness. The ice field could e.g. be created by ice management. The field’s boundaries could be seen as the transition to level ice and therefore as confinement. The simulator engine has been developed by Ivan Metrikin et al. and a description can be found in Metrikin et al. (2013). In the simulation the body is regarded as rigid body with six degrees of freedom. Metrikin et al. (2013) described the rigid body movements by the Newton–Euler equations with $M(\ddot{q})$ as the generalised mass matrix, as defined in (6). The notation follows Fossen (2011).

$$M(\ddot{q})\ddot{u} = \ddot{g} (\ddot{q}, \ddot{u}, t)$$  \hspace{1cm} (5)

$$M = \begin{bmatrix} mI_{3x3} & 0 \\ 0 & I(Q) \end{bmatrix}$$  \hspace{1cm} (6)

The used coordinate system is shown in Figure 6 with the z-axis pointing down. At each time step the ice- and fluid loads are calculated and the Newton-Euler is integrated to obtain the updated positions, velocities and accelerations (Metrikin et al., 2013). Especially the velocity- and acceleration measurements are of interested because they are given by an INS of a ship.
Simulation setup
The object was towed with different velocities through the simulated ice field. The structure has the following properties:

<table>
<thead>
<tr>
<th>Table 1: Structure properties</th>
<th>Table 2: Ice field power distribution properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>Domain length</td>
</tr>
<tr>
<td>160 m</td>
<td>2000 m</td>
</tr>
<tr>
<td>Width</td>
<td>Domain width</td>
</tr>
<tr>
<td>130 m</td>
<td>800 m</td>
</tr>
<tr>
<td>Height</td>
<td>Concentration</td>
</tr>
<tr>
<td>75 m</td>
<td>0.85</td>
</tr>
<tr>
<td>Draught</td>
<td>Beta</td>
</tr>
<tr>
<td>37.5 m</td>
<td>2.5</td>
</tr>
<tr>
<td>Structure Mass</td>
<td>Minimum MCD</td>
</tr>
<tr>
<td>959,400 mt</td>
<td>10 m</td>
</tr>
<tr>
<td>Radius of Gyration</td>
<td>Maximum MCD</td>
</tr>
<tr>
<td>43.3 m, 51.0 m, 59.5 m</td>
<td>350 m</td>
</tr>
<tr>
<td></td>
<td>Ice thickness</td>
</tr>
<tr>
<td></td>
<td>1.00 m</td>
</tr>
</tbody>
</table>

The ice field can be created by using a power distribution function.

\[ P(D) = \alpha \cdot D^{-\beta} \quad (6) \]

The parameters of the power distribution function are selected as follows. The resulting ice field is shown in Figure 6.

![Ice field for simulation](image)

Figure 6: Ice field for simulation

Velocity measurements
The moments of interaction of the structure with the ice floes become already visible in the plain linear velocity data, as shown in Figure 7. In addition, the angular velocities depend on the ice floe interaction and the speed of impact. Figure 8 shows the angular velocities. The ice interaction starts after the object has reached the x-distance of 140 metres. The reason is that in the first 200 metres there are no ice floes present. Since the object is 160 metres long and the distance is measured from the centre of gravity, which is in the middle of the object, the first ice interaction can be observed at the x-distance of 140 metres. This becomes especially obvious in the yaw velocity. Because the object can rotate, a yaw moment can be induced by the ice floe...
interaction. The faster the speed, the higher the induced yaw moment. The maximum travelled distance of the structure was 420 metres.

Figure 7: Linear velocities of the structure inside the ice field

Figure 8: Angular velocities of the structure inside the ice field

Absolute peak value distribution
The pitch velocity shows a periodic behaviour with peak values depending on the travelled velocity. A histogram analysis has been conducted to underline the velocity dependency of the roll movement. The analysis is shown in Figure 9. The peak value distribution shifts towards higher pitch velocity values for higher travelling speeds.
Correlation analysis between roll velocity and induced ice moments

The accelerations measured on the structure and the forces and moments of the structure-ice interaction are closely correlated as shown Figure 10. At a delay of $\tau = 0$ s all linear and angular accelerations show the highest correlation factor, which proofs a significant correlation.

Power spectral density analysis

As mentioned, the power contribution to the overall power of the signal for each frequency can be evaluated by the power spectral density. Especially interesting is the frequency at which most power is transferred onto the structure or ship. If this frequency is close to the natural frequency of the structure, the ice load can cause significant oscillations, which has to be damped or otherwise compensated. The power spectral densities for the pitch- and roll
acceleration are presented in Figure 11. In both cases a peak at a frequency of 0.5 Hz is observable for all velocities. The linear accelerations in x- and y-direction do not show a significant frequency. The linear acceleration in z-direction shows as well a significant frequency at 0.5 Hz as can be seen in Figure 12. The amplitude of the power induced at this frequency however depends on the predetermined speed of travel, however the measurements with 0.75 m/s do not fit into the scheme. The reason is, that at this speed high roll and pitch oscillations occur as presented in Figure 8. These oscillations can be caused by an “unlucky” pattern of ice floe hitting during the passage through the ice.

Figure 11: Power Spectral Densities for pitch- and roll acceleration

Figure 12: Power spectral density for z-acceleration

Conclusion
With the power spectral analysis of acceleration signals, a promising approach has been presented to evaluate the severity of ship-ice interaction. It has been pointed out, that the acceleration and velocity measurements, which are given by an inertial navigation system are usable for power spectral analysis because the acceleration measurements and acting ice forces are highly correlated. The results of a simulated run through the ice field with randomly sized ice floes have been presented. The simulation study cannot yet simulate a ship’s behaviour in sea ice. It serves as a proof of concept, that the velocity- and acceleration measurements provided
by an intertial navigation system can be used for ship-ice interaction evaluation by applying frequency analysis techniques. A significant frequency in the power spectrum has been found for pitch-, roll- and heave acceleration. The amplitude of the power transfer at this frequency is speed depending. Further simulations are in preparation and a sensor model with artificial disturbances on the sensor readings will be used to test the usability of power spectral analysis for field conditions. The rigid body will be replaced with more realistic ship-formed and buoy-formed bodies. In future version of the ice field simulator the brittle behaviour of the ice floes during ship-ice interaction will be included. This is not the case yet.

REFERENCES


FOSSEN, T. I. 2011. Handbook of Marine Craft Hydrodynamics and Motion Control, West Sussex, John Wiley & Sons Ltd.


APPENDIX

Power spectral densities

Figure 13: Power spectral density for x-acceleration

Figure 14: Power spectral density for y-acceleration

Figure 15: Power spectral density for yaw acceleration