Propeller-ice impacts measurements with a six-component blade load sensor

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ABSTRACT

The impact of ice on a propeller is a complex process, which most likely results into a milling or crushing process, or a combination of both. The highly dynamic forces during an impact can change rapidly in amplitude as well as direction. Little information can be deducted from conventional test setups with rigid propellers, especially forces on the individual blades are seldom successfully measured. The presented paper will outline the challenges which need to be overcome to measure these impacts and present results of actual propeller ice impact measurements.

Classic designs for propeller testing involve rigid propellers with force measurements located at the base of the propeller. From this type of setup, two problems arise. First of all, the blade area and the size of the impacted ice can be similar. Even in the case of a high quality measurement, it will be hard to derive which part of the measured forces contributes to which blade. Secondly, in practical test situations the natural frequency of the entire propeller mounted on a force transducer can be relatively low. Impacts contain high frequency energy, causing the entire propeller assembly to vibrate and thereby obscuring a correct measurement of the impact loads.

A measurement setup has been designed to overcome both problems. Rather than all four blades, only a single blade is mounted on the force transducer. This particular force transducer is capable of measuring forces in six degrees of freedom. The other propeller blades are mounted directly on the shaft. This measurement setup enabled MARIN to overcome the first problem, any impact visible in the measured signals are solely due to forces on the instrumented 'key' blade.

In AARC's ice basin a series of tests were performed where propeller ice impacts were measured. Synchronised high speed video recordings were used to gather more insight in the complex phenomena that occur during these short events.

Keywords

Propeller, Ice, Impact, Blade load.

1 INTRODUCTION

Ice loads on the propellers of pods are the focus of one of the MARIN "Cooperative Research Ships" working groups. The CRS ProPolar work group is a continuation of the S-SHIPEX and Loads on Pods working groups, which addressed global ice loads on podded ships and the hydrodynamic loads of podded propulsors (Hagesteijn 2009). Aiming to develop an analytical model to determine the ice loads on podded propulsors, model test results of propeller-ice impacts were required to validate analytical models. The analytical models are based upon the latest rules as described in IACS US 13 (IACS 2007). Formulations for PODs where derived by using the scarce available full scale data. Support of the selected methods, with use of more detailed measurements is therefore needed. It would be preferred to do these measurements at full scale, but due to limitations and constraints in various areas, this is hardly achievable, and model tests become an attractive alternative.

Measuring ice impacts on model scale faces some specific challenges. To determine the ice loads on a propeller, a model test setup had to be designed, capable of measuring the impact of ice on a propeller by means of measuring the highly dynamic forces and moments in all directions. This setup has been extensively calibrated and tested in controlled conditions. Finally, the setup was used for actual ice impact measurements in cooperation with AARC of Helsinki. AARC's hi-tech ice tank was used to measure propeller-ice impacts including synchronized, high-speed video recordings, which gave a unique insight into the propeller ice contact and the corresponding loads.

2 WHAT ARE PROPELLER-ICE IMPACTS?

The first challenge one encounters when trying to measure propeller-ice impact loads is the question what to expect? Today's predictions are based on scarce measurement data and empirical models. In the 80'ies full scale measurements on individual blades were attempted (Antonides 1981). Various model tests with stylized blade impacts have been undertaken to study the various phenomena over the past decades. In 2002, model tests were performed with an instrumented blade on a model propeller (Moores 2002). Some of this data provides an idea of what forces to expect.

Propeller-ice impact loads are normally considered to mainly origin from three separate mechanisms and combinations of these.

- Hydrodynamic suction force, caused by blocked water inflow due to the presence of an ice block near the blade
- Propeller cutting or milling the ice which partly cracks or crushes typically in the nose region of the blade
- Ice pressure on the blade surface which normally occur when crushed ice is squeezed between the blade and the ice block

All of these loads may be present during one ice impact and their behavior is very dynamic and changing in a short time span.

A more detailed description of the different ice load scenarios is presented by Norhamo et al (2009). Features which are very important are the short duration of peak impact loads and the severity of this peak load. The challenge presented in here is to make sure that the correct peak load is measured, no matter how short the duration is.

3 CHALLENGES OF MEASURING PROPELLER-ICE IMPACTS ON MODEL SCALE

To measure ice impact loads correctly, the setup for such measurements should be capable of measuring the high impact load of an ice-sheet or ice-piece on a propeller by means of measuring the forces and moments on a propeller in all directions. The starting point for this measurement campaign was to use a setup of a propeller mounted on a so-called ‘six degree of freedom’ or ‘6DOF’ force transducer which measures forces in x-, y- and z-directions as well as moments around the x-, y- and z-axis. With this kind of set-up experience was already available from the oblique open water tests which were carried out for several research and commercial projects. In these tests the loads in all 6 degrees of freedom were measured for a complete propeller model at several angles of attack.

A few problems immediately arise from this concept. The size of the impacted ice can be relatively large compared to the dimensions of each individual blade. For example, if one blade is entering the ice with its leading edge, another blade may as well have direct ice contact with an ice floe somewhere on a propeller blade section. In this situation, the individual blade loading cannot be determined from the measured overall loads since the individual blade loads overlap.

For propeller-ice impact tests a best option has to be selected to conform to the different applicable scaling laws (Vroegrijk 2011). For this kind of tests, Froude scaling is applied combined with Cauchy scaling, see Equations (1) and (2) respectively.

$$U_M = \sqrt{\lambda^{-1}} \cdot U_F \quad (1)$$

Where λ is the scale ratio, U is the velocity, subscript M denotes model scale and subscript F denotes full scale.

$$E_M = \lambda^2 \cdot \left(\frac{\nu_M}{\nu_F}\right)^2 \cdot \left(\frac{\rho_M}{\rho_F}\right)^2 \cdot E_F \quad (2)$$

Where λ is the scale ratio, ν is the kinematic viscosity, ρ is the density, E is the Young's modulus, subscript M denotes model scale and subscript F denotes full scale.

The scale factor λ is determined by the geometrical properties of the model. Froude scaling dictates velocities should increase with a factor of the square root of λ. To ensure correct scaling of the Young’s modulus, Froude combined with Cauchy dictates that the strength of the ice should decrease by a factor λ. This method of scaling is applied in most ice basins.

The scaling of velocities poses another problem, which is the natural frequency of the system. Due to the scaling laws as described above, a target rotational velocity of around 700 rpm is intended. Without any knowledge of the specific impact forces, a minimum frequency of interest can be deduced. A typical propeller design for ice has 4 blades. With a rotational speed of 700 rpm, the number of impacts per second is around 47 Hz. This immediately implies that the natural frequency of the measurement setup should be multiple factors higher in order to measure an individual impact and it’s details.

4 MEASURING HIGHLY DYNAMIC PHENOMENA

The measurement of a short duration impact load requires some elaboration. In common measurement setups, natural frequencies of measurement devices tend to be very high with respect to the phenomena of interest. Apart from issues related to basic measurement uncertainty, the dynamic range of the measurement device will generally be much higher than the frequencies of interest and therefore not be an issue. However, when measuring propeller-ice impact loads, the natural frequency of the measurement setup becomes critical. To illustrate this, it is useful to consider the design of common propeller force measurement setups and compare these type of setups to a mass-damper-spring system.

A typical force measurement of propeller loads in pods will look as depicted in Figure 1. The propeller is directly mounted on a transducer with part of the transducer located within the propeller hub. The transducer is mounted on the rotating parts of an electric motor. No gears or means of physical power transport are applied.

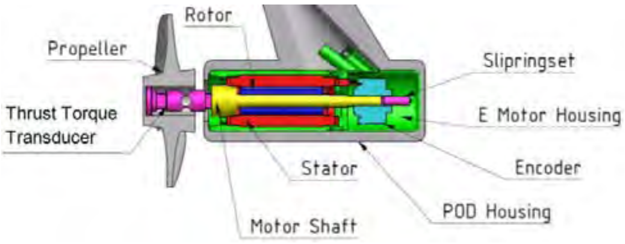

Figure 1: schematic of a propeller load measurement setup in a pod

The analogue to a mass-damper-spring system can be used to describe the physical behavior of the setup. In Figure 2, a mass-damper-spring system is illustrated.

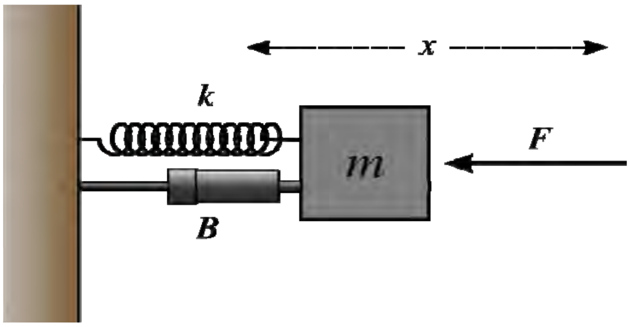

Figure 2: schematic of a mass-damper-spring system, picture courtesy of Ilmari Karonen (2005).

The analogy with the propeller measurement setup is as follows: the spring, denoted by k, is similar to the transducer, a relatively weak part of the setup. The rotating parts of the electric motor can be thought of being the fixed base in this case, denoted by the brown wall on the left. The propeller itself has a significant mass, similar to the mass m in the system. The force applied, denoted by F, is the ice impact load to be measured. The response x is actually measured by the strain gauges located in the transducer. Steady measurements provide a perfect linear relationship between the measured response x and the applied force F. The difficulty for dynamic measurements is that the response function deviates from this perfect linear relationship with higher frequencies.

To demonstrate the influence of various system configurations on the measured signal, two simulations of mass-damper-spring systems are demonstrated. Equation (3) is the governing differential equation for this type of problem.

$$m \cdot \ddot{x} + B \cdot \dot{x} + k \cdot x = F \qquad (3)$$

Where m is the mass, B is the damping constant, k is the spring constant, x is the displacement from equilibrium with and $\dot{x}$ and $\ddot{x}$ it's first and second time derivatives. F is the applied force.

The natural frequency of such a system is described by Equation (4).

$$\omega_0 = \sqrt{\frac{k}{m}} \qquad (4)$$

Where k is the spring constant, m is the mass and ω is the natural frequency.

It is expected typical force phenomena of impacts are well within the 0.01 seconds range. Therefore an impact with the shape of a step function is simulated to represent a possible ice impact. The signal which would be recorded at the position of the transducer is calculated and presented in the same figure with the input signal. Also a filtered result is drawn which makes sure the natural frequencies of the system are removed from the result.

Figures 3 and 4 show the simulation results. Figure 3 shows an undesirable configuration which produces inaccurate results when measuring short duration impacts, while Figure 4 shows a more desirable configuration. The system from Figure 3 has a low natural frequency (25 Hz) and relatively high damping. The system in Figure 4 has a much higher natural frequency (500 Hz) and also a lower internal damping.

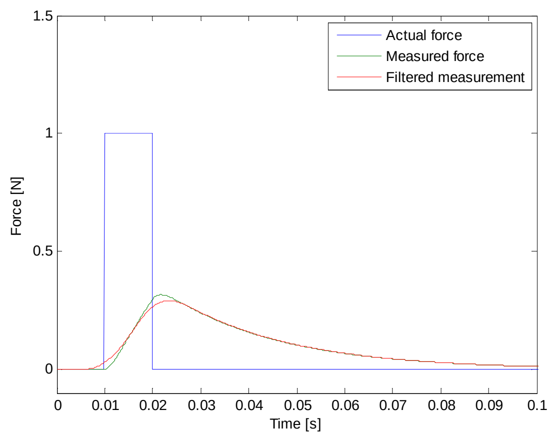

Figure 3: simulated system response, undesirable setup

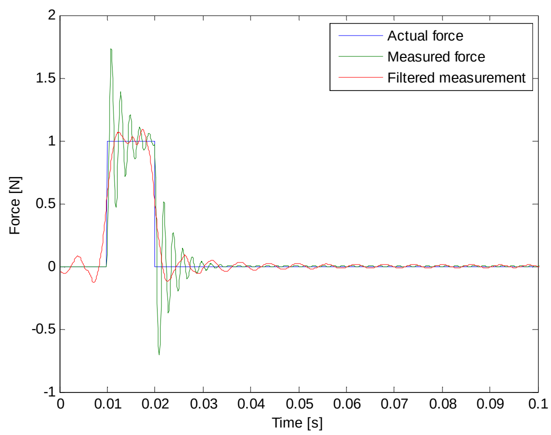

Figure 4: simulated system response, desirable setup

It is observed that the simulation of the undesirable setup does not register the peak value, nor the time of occurrence. Also the duration of the impact is exaggerated. This is due to the natural frequency of the measurement setup being lower than the duration of a typical impact phenomena.

The more desirable setup shows almost five overshoots of the measured signal during the period of the applied force and a too high peak value. This drawback however is improved upon by applying a low pass filter during post-processing. This filter makes sure the peak value is registered more accurately. The overshoot of the unfiltered signal over predicts the peak by almost 75% while the filtered overshoot is limited to the range of 5% to 10%. In Figure 5, the frequency amplitude response of the simulation in Figure 4 is drawn.

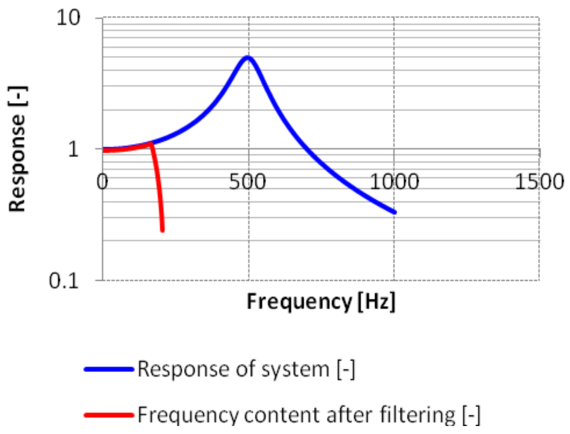

Figure 5: simulated system response, frequency diagram

For low frequencies, the ratio between response and excitation force of the system is close to unity and will follow the normal calibration of the transducer. When moving to the natural frequency, the response is exaggerated multiple times. After the peak response, the response decreases rapidly. The system now behaves as an analog low-pass filter, not registering any of the higher frequencies. Filtering the measured response far below the natural frequency ensures that any signal shown is an accurate representation of the actual force at that particular frequency without overshoots.

To ensure the registration of all phenomena or as much as possible during a propeller-ice impact, it is aimed to have the natural frequency of the system and hence, the applied filter frequency, as high as possible.

5 SETUP AND VALIDATION TESTS

Using this theoretical background information, a setup for measuring single propeller blade loads was engineered, using FEM calculations to ensure that the set requirements with regard to natural frequency are fulfilled, see Hagesteijn et al (2012). Furthermore, requirements for the typical environmental conditions, such as low temperature and salinity of the water were adapted in the design. Figure 6 shows a CAD drawing of the final design.

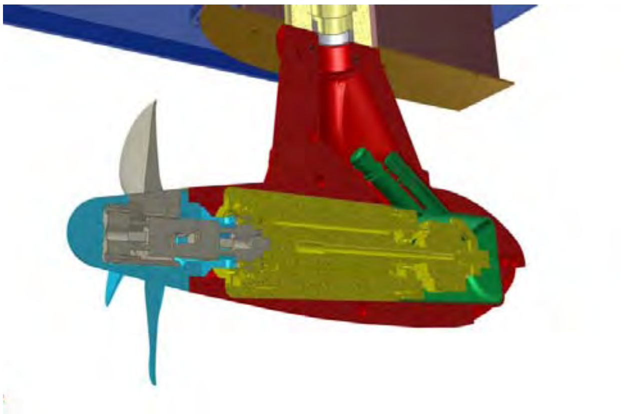

Figure 6: cross section of measurement setup

When the test set up was made, one of the most crucial phases started, being the validation of it. Therefore extensive tests have been performed at MARIN to study the response of the measurement system. For the static response of the system various static load tests have been performed.

The study of the dynamic response is more challenging. Various tests in air and in water with varying rate of revolutions have been performed. One test in particular demonstrates the capability of the setup. The test consisted a ‘hammer’ test in a small tank filled with water while the rate of revolution is 300 rpm. The propeller blades were hit with a soft piece of foam, see Figure 7.

Figure 7: foam for the ‘foam-hammer’ test

The torque signal of the 300 rpm foam test suspended in water is shown in Figure 8. The figure also shows the rate of revolutions during the test. Until 15 seconds the propeller is turning undisturbed. Between 15 and 17 seconds the piece of foam is pushed against the blades, resulting in 12 impacts on the key-blade. After that, the foam is released again.

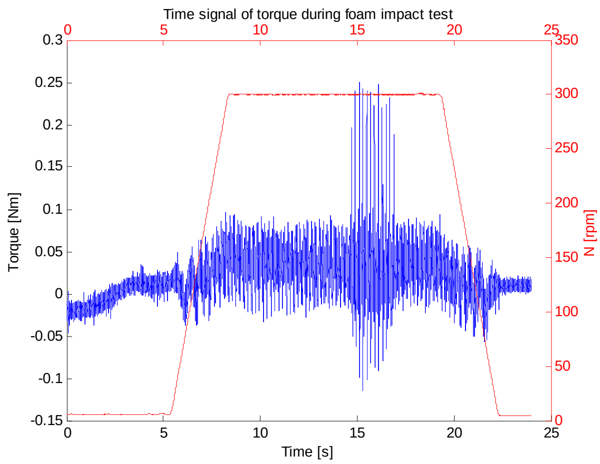

Figure 8: torque and rpm during the ‘foam-hammer’ test

In Figure 9 the time series around one of the impacts is enlarged.

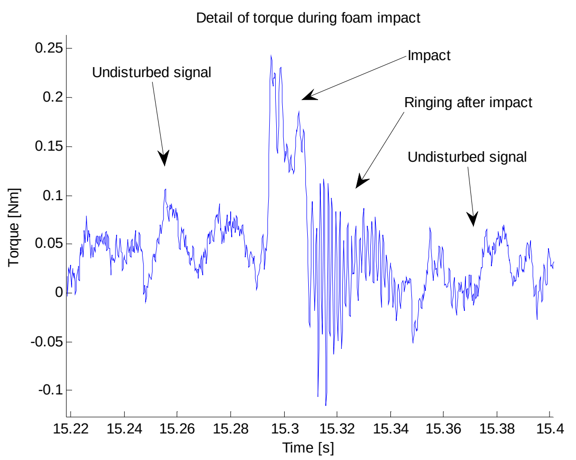

Figure 9: torque signal during the ‘foam-hammer’ test

Four distinct areas can be identified. In the first and fourth area, the key-blade is only in contact with the water surrounding it. The deviations on the signal are due to engine vibrations, thermal noise on the signal or other external factors. The second area is the actual impact. The third area shows the signal directly after the release of the foam. During this period, the foam is suddenly released from the key-blade and the key-blade starts ringing as demonstrated before in Figure 4.

To check whether the natural frequencies predicted are correct, a spectral analysis is performed. The results are shown in Figure 10. Indicated by red lines are the first 4 natural frequencies of the setup as predicted by FEM calculations. The part left of the first natural frequency is considered to contain the measurement data of interest. In the middle of the spectrum are 3 clearly identifiable peaks which closely correspond with the initially calculated natural frequencies, proving that the setup behaves as predicted.

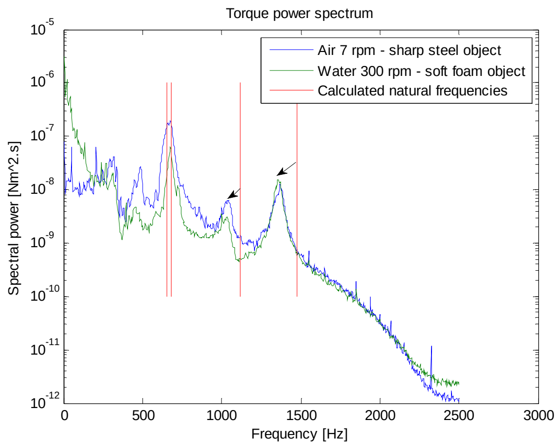

Figure 10: spectral analysis results

Since the first natural frequency of the setup is proven to be above 650 Hz, it is opted to use a low pass filter with a cut-off frequency of 300 Hz for this setup to ensure peak values measured have no large overshoots. The effect of such a low pass filter is shown in Figure 11.

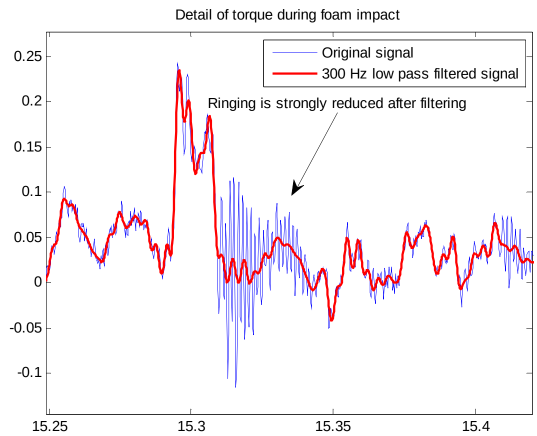

Figure 11: unfiltered and filtered torque, detail

The same detail as in Figure 9 is shown. The ringing which was present before and caused an overshoot is now removed from the result.

6 TESTS IN ICE

The final design as tested in the AARC ice facility is shown in Figure 12. The key-blade is indicated by the black lines. A small gap can be seen between the base of this key-blade and the hub connected to the other blades. This gap is to ensure no loads of the key-blade are accidently transferred to the hub and the engine shaft.

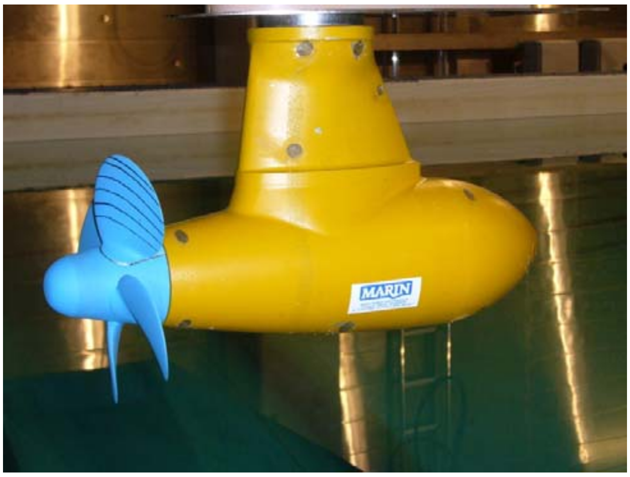

Figure 12: measurement setup in ice basin

Tests were carried out during several days for various ice conditions and different types of encounters of the pod with the ice. Apart from measuring forces on the key-blade, high-speed video recordings were made synchronously during the tests to allow better understanding of the impact mechanism of ice on the propeller blades, see Figure 13.

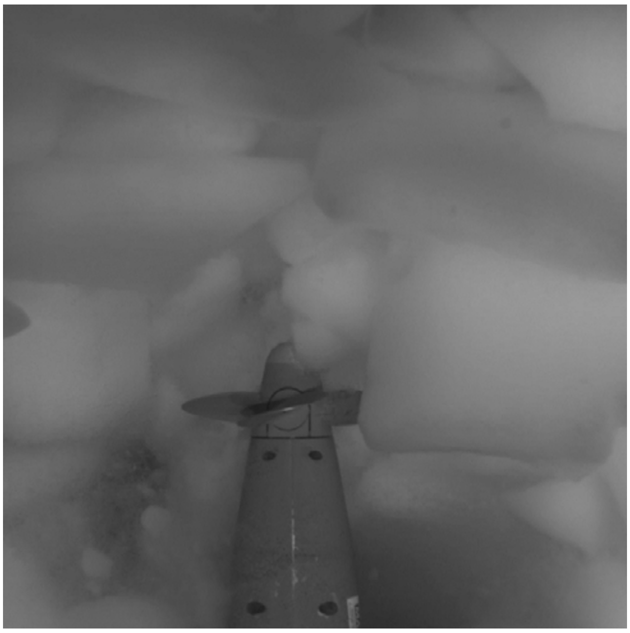

Figure 13: still from high speed camera with propeller entering an ice ridge

The data of the ProPolar project is proprietary to the CRS and therefore only scarce results can be shown in this paper. An example of a recorded impact is presented in Figure 14. The propeller blade hits the ice three times in a row. The first impact is the largest and it can be seen that the thrust of the propeller blade becomes negative, hence the ice is bending the propeller blade backward.

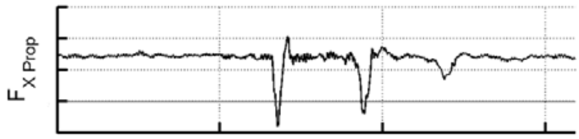

Figure 14: time trace of Fx, where propeller blade hits the ice three times

In the presented time trace it can be seen that the period that the propeller blade is in the ice is very similar but that the loads reduce during the process. The horizontal part represents the open water loading condition of the propeller blade.

The propeller itself will encounter more than three hits as it has four blades. Since the key-blade was isolated from the other blades, it cannot be determined how other blades have hit the ice during a single test.

Apart from the magnitude of the ice impacts, also the point of application of these impacts is necessary input for load and fatigue calculations. With the forces and moments known in 6 degrees of freedom, an application point can be determined for this force. More accurately, a line of application can be determined which intersects with a surface. The surface chosen is a 2D representation of the blade for easiness of calculation. The line of application is defined as the line were the translated force vector would have a minimized (or zero) resulting moment left. The direction of this line is always parallel to the direction of the force vector itself. The intersecting point with the surface is determined by finding the solution with zero moments applied perpendicular to this line. However the moment applied over the longitudinal direction of the line itself stays the same, regardless of the position of this line in space. Therefore the minimum total moment found can be different from zero. An example is shown in Figure 15.

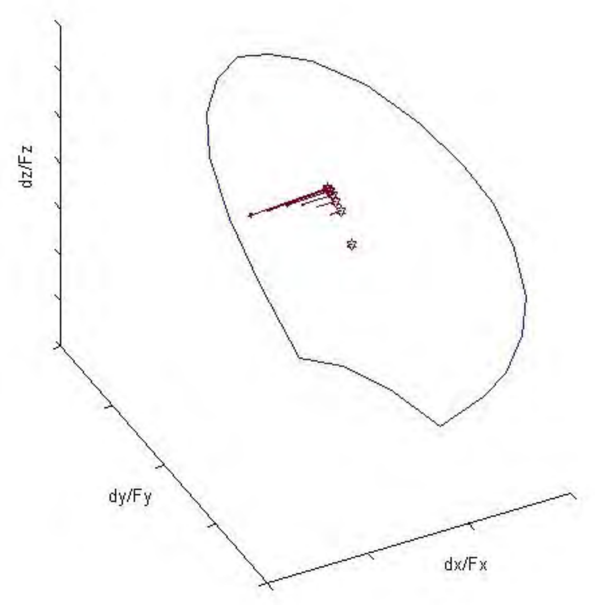

Figure 15: example of application point of forces

Figure 15 shows the application point of forces for several bollard pull open water tests, which are also depicted as the 'separable loads' during ice impact tests. The length of the arrows indicate the size and direction of the force. The rate of revolutions was increased in several steps. It is observed that with higher rate of revolutions the point of application converges. Probably due to viscous effects, the flow around the blade is different at lower rate of revolutions and hence the point of application is closer to the blade root. The application point technique was also successfully utilized to determine the application point of the ice impact contribution or inseparable loads.

This, combined with synchronized high speed video recordings enables the analysis to distinguish between hydro-dynamical disturbances before ice impact, ice impact loads and the hydrodynamic disturbances after impact. Statistics derived from this analysis can then for example be compared with some of the scarce available full scale data sets, such as described by Jussila et. al. (1989) which analyzed a large full scale data set and derived not only impact locations but also statistics from the measured time series.

8 CONCLUSIONS

Measuring propeller-ice impacts is a challenging task. The design of the test setup that is presented in this paper shows the long development route that has been taken to come to a successful design. It started with an investigation of the identity and signature of the loads that had to be captured. Propeller-ice impacts are highly dynamic conditions where time, amplitude and direction are constantly changing. This requires a good estimation of a sufficient measurement range to capture the driving phenomena. Assessment of the natural frequency of the design of test set is required to assure the establishing of a setup that is able to measure impact loads at the foreseen frequency range.

Fitting a single propeller blade on a 6 degrees of freedom force and moment transducer, allows the identification of the impacts on one single blade. With the use of finite element method calculations, the bending modes and their corresponding natural frequencies of the setup were calculated. Static calibration tests and dynamic performance tests showed that the acquired natural frequency of the setup was following the lines of expectation.

The test setup was used in the AARC ice facility for a successful series of real model ice tests. Ice impacts could clearly be recorded with the instrumented 'key-blade'. From these recordings, statistic profiles for certain types of impacts could be derived. With the attained accuracy, it was possible to determine point of application of both the open water part (separable loads) and the ice impacts (inseparable loads).

The time traces, statistics, point of applications and synchronized high speed videos combined proved to be a unique data-set for the CRS Propolar working group.

9 ACKNOWLEDGMENTS

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