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Quantification of Cavitation Impacts with Acoustic Emissions Techniques

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ABSTRACT

Cavitation erosion on propellers and rudders remains a problem in the marine industry. The consequences of failing to detect the risk of erosion damage during the design phase, and early in the service life of a vessel, include reducing the speed of the vessel, unscheduled dry-dockings and repairs or replacement of the propellers or rudders. The associated costs are borne by the builder and owner and may harm their reputations within the industry.

Lloyd’s Register has developed and tested a unique measurement system, based on acoustic emission techniques, which is capable of detecting the onset of erosion damage on propellers and rudders. The system uses high frequency transducers to quantify the impulsive energy transmitted from imploding cavitation events through the material paths of rudder, propeller and shafting configurations. The acoustic emission signals from such events have been synchronised with visual observations using high speed video equipment and borescopes.

INTRODUCTION

Cavitation erosion on propellers and appendages, in particular rudders [1], remains a problem in the marine industry. Erosion damage requires increased maintenance including more frequent monitoring of the damage, dry-dockings and repairs and can limit the operational profile of a vessel. The associated additional costs are borne by the ship owner and ship builder.

Erosion damage occurs as a result of failures to identify erosive cavitation characteristics during the project design phase. It is difficult to assess the erosive potential of cavitation from calculations and model tests, even when using the current, qualitative, paint and observational techniques [2].

When a vessel enters service, (underwater) inspections may not identify erosion damage until after the incubation period, when the surfaces have started to break up. Therefore, damage may not be discovered until or after the guarantee dry-docking limiting palliative action by both builder and owner. Moreover, when erosion occurs it can be difficult to answer some of the questions that would help to create a better understanding of and allow better control of erosion. If the exact conditions and phenomena that lead to erosion were known, full scale observations and model tests could be interpreted to modify the design and avoid erosive cavitation. Alternatively, this information could be used to change the operating profile in order to minimize erosion damage. To this end Lloyd's Register has developed a condition monitoring capability for erosion damage from cavitation which is based on acoustic emission techniques.

MEASUREMENT TECHNIQUE

Lloyd's Register has been using and developing acoustic emission techniques over the past 12 years [3]. This technique relies on high frequency sensors that detect wide band stress waves travelling through a structure, referred to as acoustic emissions. Typical sources of acoustic emissions include crack growth and metal to metal contact, hence Lloyd’s Register has used this technique extensively to monitor crack growth in, mainly, metallic structures and for the condition monitoring of rotating machinery. However, it was found that cavitation impacts also give rise to such acoustic emissions which travel through physical connections to locations inside the ship. Acoustic emission sensors can easily be installed inside the ship and used to monitor and quantify such cavitation impacts.

LICHTAROWICZ CELL

The feasibility of using acoustic emission techniques to detect cavitation erosion was first shown in tests in a Lichtarowicz cavitation cell in work carried out for the EROCAV project. In a Lichtarwicz cell, shown in **Figure 1**, a cavitating jet impinges on a specimen causing erosion. By varying jet and chamber pressures and the distance between nozzle and target, different impact intensities can be created.

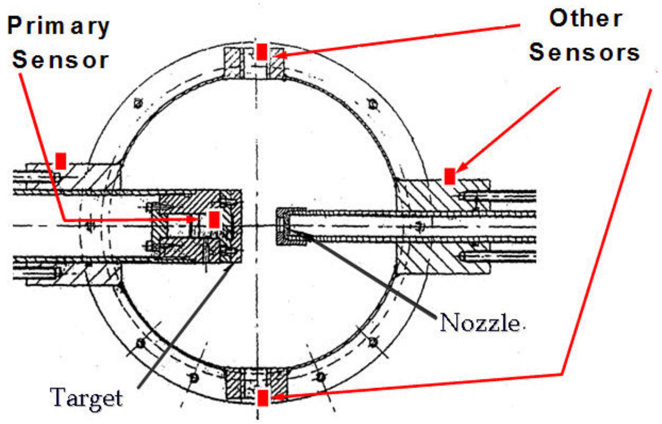

Figure 1, Test set up in Lichtarowicz cavitation cell

The Lichtarowicz cell was fitted with a primary acoustic emission sensor at the back of the target specimen, and a number of secondary sensors on the walls of the cylindrical tank. Acoustic emission energy was recorded at a number of different conditions and compared with mass loss rates measured by Momma [4].

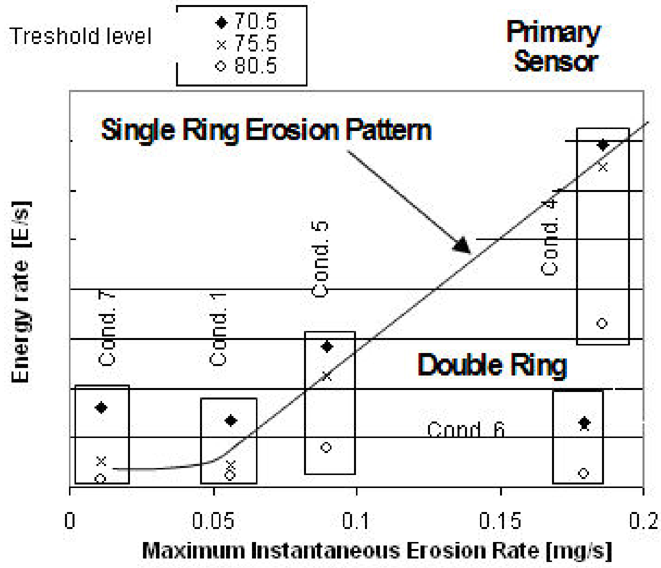

Figure 2, Correlation of acoustic emission energy and erosion rate

The results, in **Figure 2**, show there is a correlation between acoustic emission energy and mass loss rate and therefore acoustic emission techniques can be used to quantify the erosive potential of cavitation impacts. Furthermore, using the arrival times of acoustic bursts, it was possible to locate the impacts at the target surface giving confidence that recorded signals were a result from cavitation impacts.

SIGNAL ATTENUATION

During in-service measurements it is seldom possible to install sensors directly at the impact location as in the Lichtarowicz cell. However, as the acoustic emission travels from its origin to the measurement location, its amplitude will reduce. This attenuation can be measured using a Hsu-Nielsen source which generates a signal of known magnitude at a known location. This distance amplitude correction was measured for typical structures subject to cavitation erosion such as rudders and propellers. A propeller test set up and the result of such a test are shown in **Figure 3**.

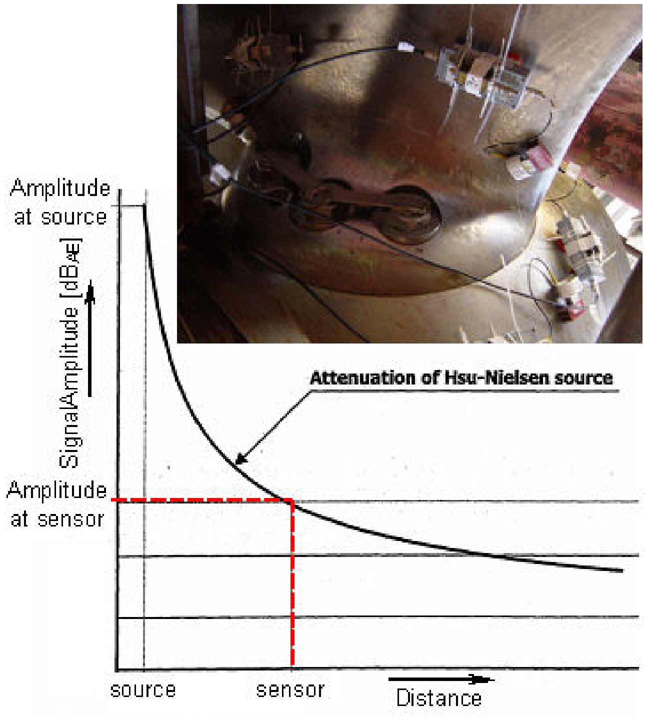

Figure 3, Test set up and measured attenuation curve

EROSION OF APPENDAGES

The erosion detection system was first used in-service on a number of rudder horns since these are easily accessible from inside a ship. Rudder horns are nearly always subject to impacts from vortex cavitation from the propeller tip and sometimes erosion occurs where this vortex meets the rudder horn leading edge.

Figure 4 shows an acoustic emission measurement and observation test set up to quantify the erosive potential of the impact of propeller tip vortex cavitation (TVC). Acoustic emission sensors are installed on the rudder horn inside the ship and a borescope observation position is located several metres off the ship centre line to provide a good view of the passing tip vortex.

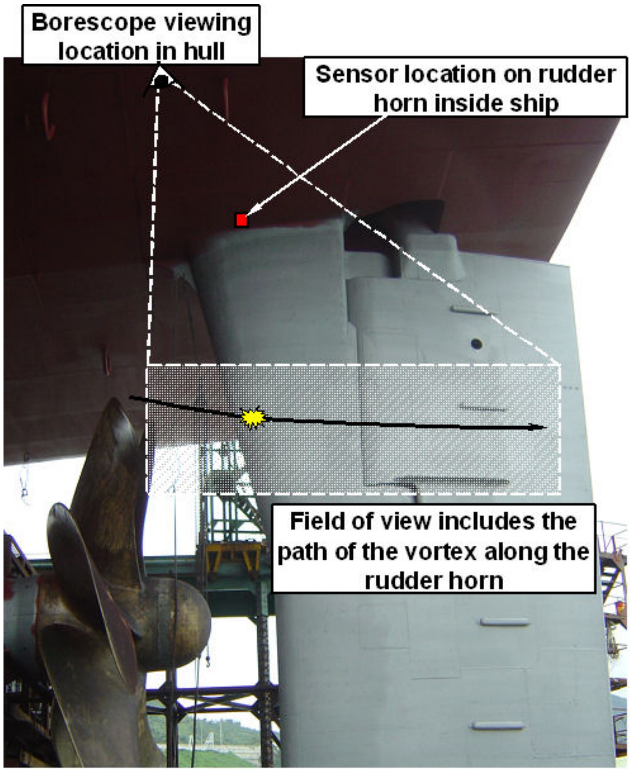

Figure 4, measurement and observation of tip vortex impact

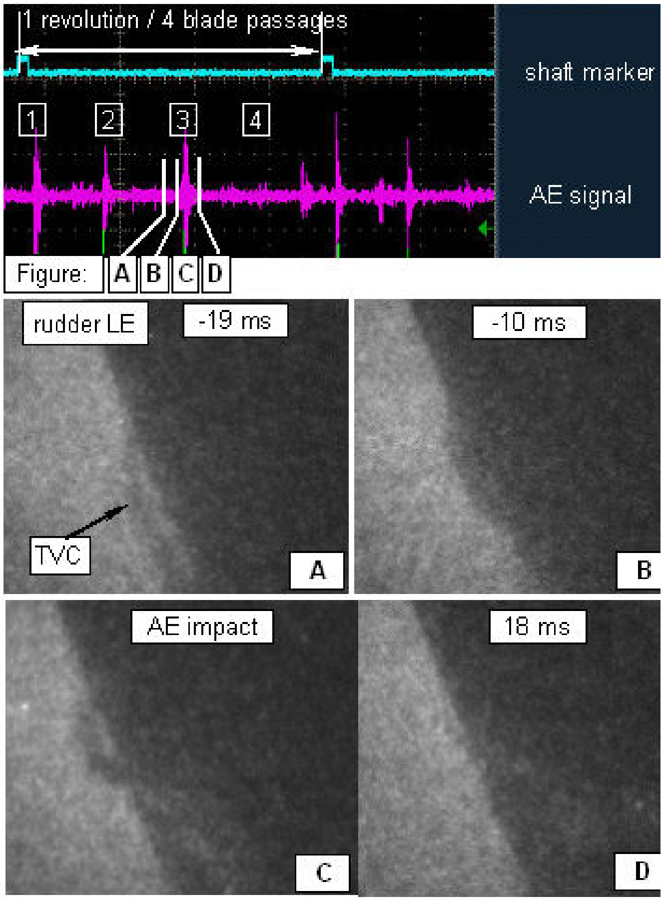

Figure 5, Simultaneous video observations and acoustic emission measurements

The acoustic emission time series in **Figure 5** exhibits a burst at every blade passage and is hence likely related to the interaction of the passing, consecutive, tip vortices (TVC) and the rudder leading edge. Simultaneous observations, also shown in **Figure 5**, suffered from a lack of light but still show that the instant the tip vortex is expected to impinge on the rudder horn (**Image C**) coincides with the acoustic emission burst. Therefore the burst will be a result of cavitation impact on the leading edge of the rudder horn. Furthermore, by installing several sensors on the rudder horn and using the arrival times of the acoustic emission, it was possible to locate the impact at the site where erosion damage was observed. These findings were consistent over tests carried out on a number of ships.

SHAFT-MOUNTED EROSION-DETECTION SYSTEM

To measure acoustic emissions from cavitation impact on a propeller a shaft-mounted erosion-detection system was developed. This system, consisting of an acoustic emission sensor, a signal conditioning unit and a telemetry set, is shown in **Figure 6** together with a schematic of the measurement set up.

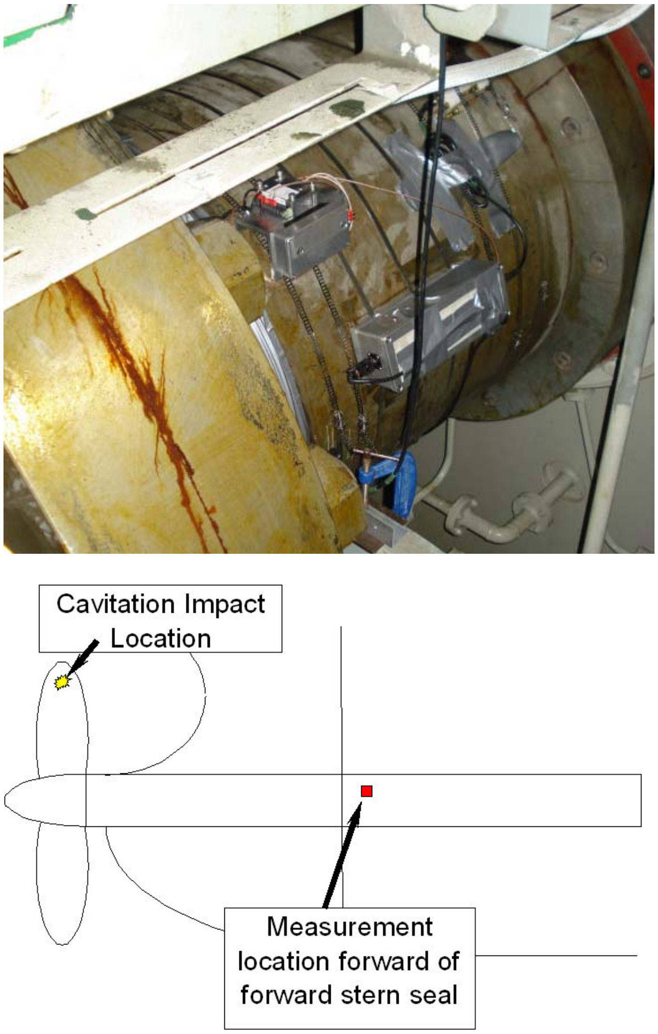

Figure 6, Shaft-mounted erosion-detection system

The ship’s engine room, due to the associated acoustic emission sources other than cavitation impact, is a challenging place for acoustic emission measurements, further complicated by the significant attenuation caused by the large distance between emission source and sensor. To evaluate this, an attenuation test was performed with a specifically designed Hsu-Nielsen source, capable of creating an acoustic emission equivalent to one from cavitation impact. These tests were performed on a berthed containership where the propeller tips only were not immersed. The majority of the blade and hub were submerged to simulate the actual conditions at which measurements would be performed. These measurements indicated that cavitation impacts on the propeller tips could be detected on the shaft inside the ship and an attenuation curve, as shown in **Figure 3**, was determined for a propeller and shaft combination.

ASSESSMENT OF PROPELLER EROSION RISK

The viability of the system to quantify cavitation impacts on a propeller was investigated on a tanker with known erosion problems. Erosion of the propeller occurred towards the “ear” of the blade on the suction side, as shown in **Figure 7**, and had grown to a depth of approximately 10mm in the first 12 months of service.

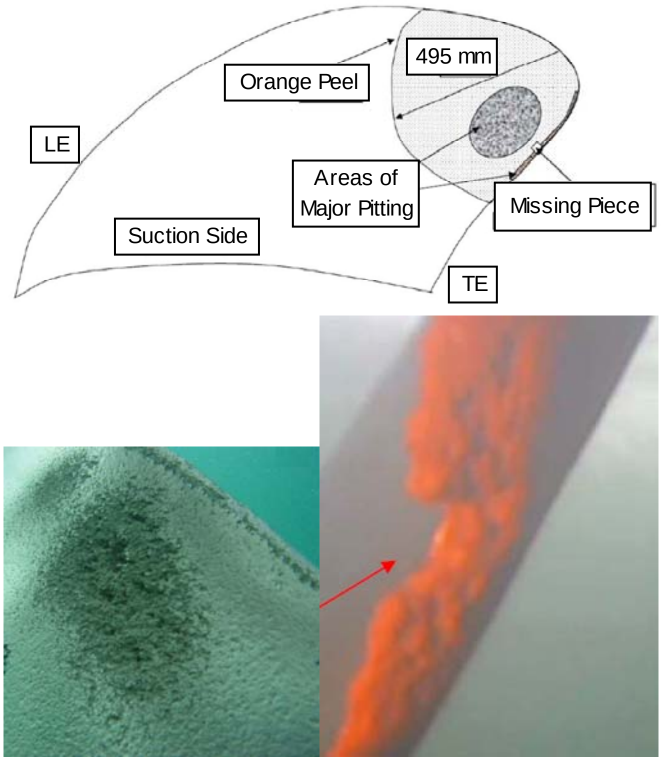

Figure 7, Erosion damage on a tanker propeller.

A propeller erosion-detection system was mounted on the shaft of the tanker, as shown in **Figures 6,** and measurements were performed in ballast and loaded condition over a range of shaft speeds. Simultaneously, high speed video observations were performed with two synchronized borescope systems from port and starboard.

Two examples of acoustic emission time series, recorded at 62RPM and 74RPM in ballast condition, are shown in **Figure 8**. At both shaft speeds the signal was periodic with the blade passing frequency which suggests that cavitation impacts on the blade were the likely source of acoustic emission. Furthermore, the direction of travel of the acoustic emission, determined by two sensors located along the shaft line, was away from the propeller which also indicated the propeller as the origin of the emission.

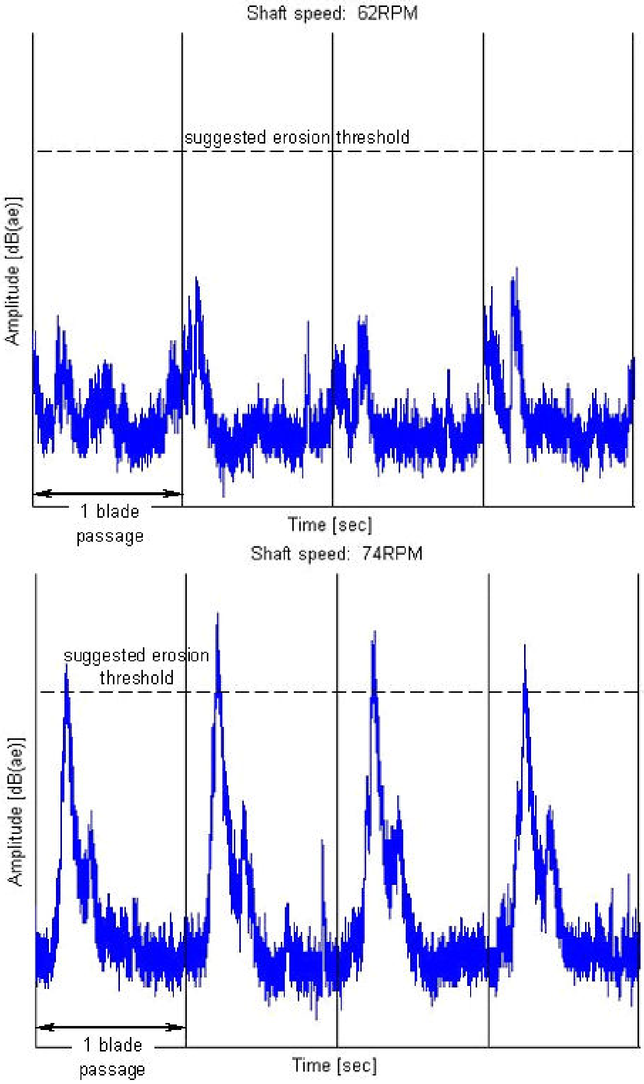

Figure 8, Recorded acoustic emissions from propeller cavitation impact

At 62RPM the signal for every blade passage showed some repeatable features with the suggestion of a burst occurring twice per blade passage. In this low power condition the cavitation volumes are likely to be small and, possibly, more susceptible to temporal variations in the wakefield. This might suppress repeatable cavitation phenomena and lead to a less periodic acoustic emission signal. With increasing shaft speed the signal amplitude increased and at 74 RPM there were two distinct bursts with every blade passage. The increased amplitude is consistent with the increased energy supplied to the cavitation, although the cavitation collapse and the accompanying impact pressures will also depend on local cavitation dynamics.

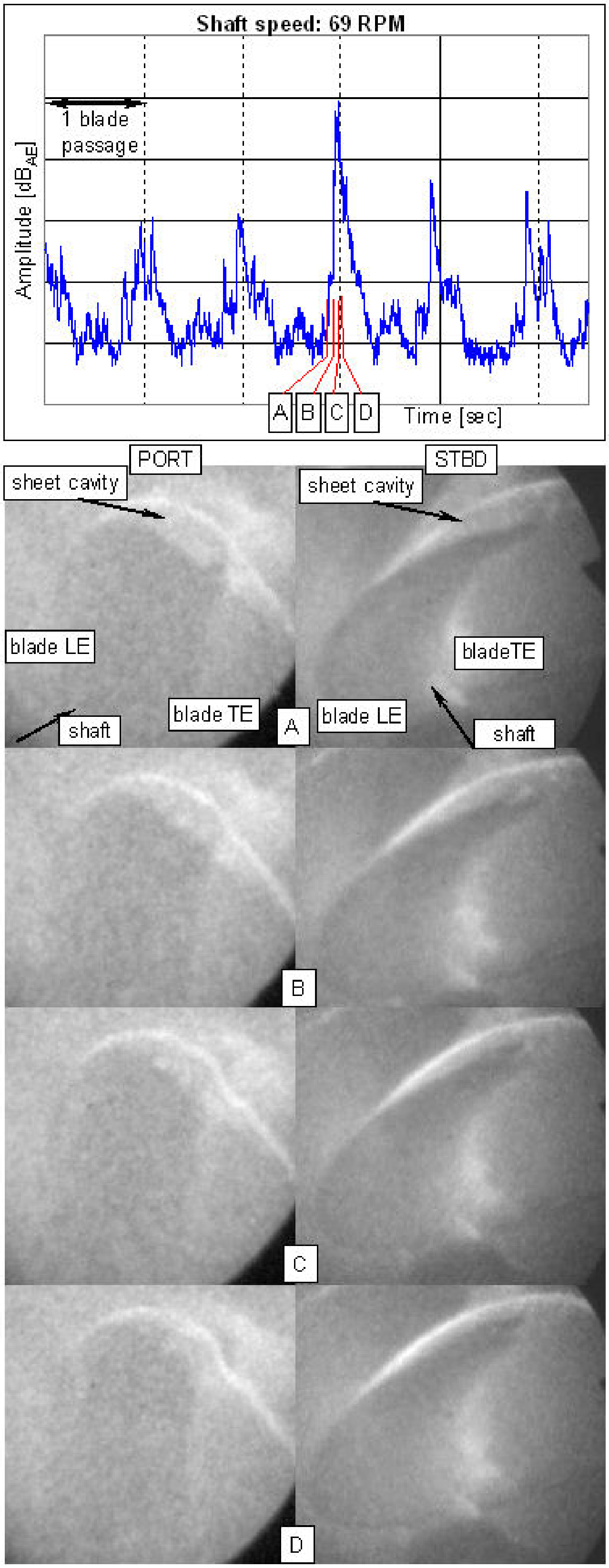

Figure 9, Recorded acoustic emissions from propeller cavitation impact

Images of the propeller were only obtained in the loaded condition since entrained air obscured the view in the ballast condition. Two high speed videos (up to 400fps) simultaneously recorded images of propeller cavitation from locations forward of the propeller, to port and starboard. A series of consecutive stills from these recordings is shown in **Figure 9.**

Images A show the blade in the 12 o'clock position where the sheet cavity extent is largest. A cavitating vortex emanates from the tip of the blade. As the blade rotates further a streak of cavitation develops as a series of cloud-like structures at the lower extent of the sheet cavity, as shown in **Images B**. The path of these clouds is consistent with the lower edge of the sheet cavity, **Images C,** and collapse occurs in a focused manner on the "ear" of the blade, which coincides with the area where erosion damage was observed in **Figure 7**. The EROCAV guidelines [2] suggest that such a separate development of cavitation contains a high risk of erosion because of its repeated and focused collapse. The cavitation moves off the blade via the blade trailing edge, **Images D**, as the blade leaves the wake peak.

Approximately 5 blade passages of simultaneous recorded time series of acoustic emission are also shown in **Figure 9**. In a similar manner to the measurements on the rudder horn, **Figure 5**, the peak in the acoustic emission signal corresponds to the moment when cavitation impact on the blade is observed, **Images C,** which gives confidence that the acoustic emission signals are indeed the result of cavitation impact. The cavitation collapse of the third blade passage in **Figure 9** gives rise to a significantly larger acoustic emission than other blade passages. Interestingly, in this sequence it was only during the third blade passage that the separate streak of cloud cavitation, thought to be responsible for erosion, was prominent. High acoustic emission amplitudes were accompanied by the separate cloud cavitation throughout the recorded data set.

The measured acoustic emissions, resulting from cavitation impact, provide information to quantify the erosive potential of cavitation. Counting the maximum peak for each blade passage in the time series signals (**Figures 8** and **9),** results in amplitude histograms as shown in **Figures 10** and **11**. These amplitude histograms reflect the energy present in the cavitation impacts at a given condition, where energy is proportional to the sum of the number of impacts times their amplitudes.

Figure 10 shows the amplitude histograms for signals recorded in the ballast condition at shaft speeds between 62RPM and 74RPM. Up to 70RPM there is a steady increase of energy, however, at shaft speeds over 70RPM the impact energy increases markedly. Relating this to the observations in **Figure 9,** one could postulate that, in the ballast condition, the separated streak of cloud cavitation that resulted in the potentially erosive cavitation impacts only develops at shaft speeds over 70RPM.

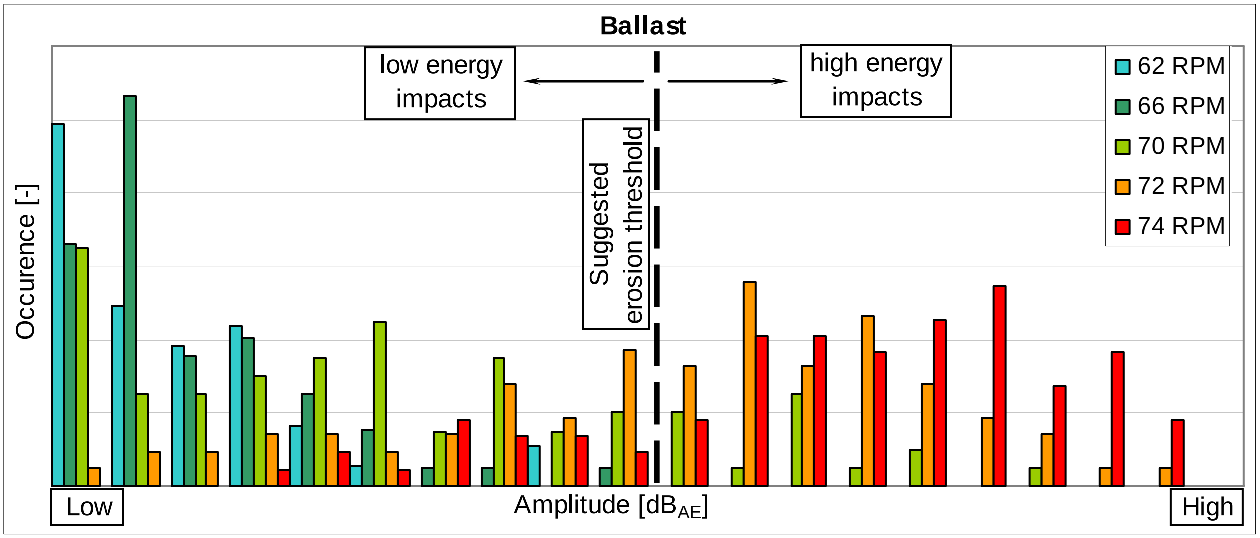

Figure 10, Maximum amplitudes per blade passage

The impact energy in ballast and loaded condition, histograms in **Figure 11**, are very similar at shaft speeds up to 70RPM. However, at shaft speeds in excess of 70RPM there are significantly more bursts with large amplitudes in the ballast condition. This suggests that the potentially erosive cavitation, as observed in **Figure 8**, occurs more frequently in the ballast condition thus making this the more erosive condition, a result which is consistent with a more dynamic cavitation due to the reduced static pressure at the propeller. This effect is not offset by a reduction in power since the ship's staff indicated a similar power was absorbed by the propeller in ballast and loaded condition.

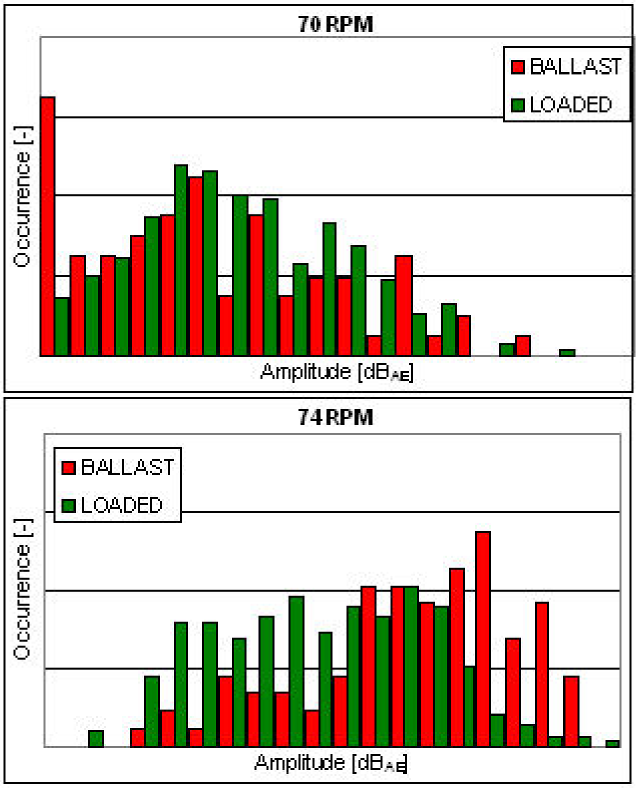

Figure 11, Impact energy in ballast and loaded draught.

CONCLUSIONS

A system to monitor cavitation erosion on rudders and propellers has been successfully developed by Lloyd's Register. The development process included feasibility studies in a Lichtarowicz cell, attenuation tests in dry-dock and afloat, together with in-service measurements on ships. In the case of a tanker, suffering from erosion, the acoustic emission system has determined the operating conditions which have produced high levels of erosive cavitation. Furthermore, the use of simultaneous high speed video recordings synchronised with acoustic emissions signals has determined with greater certainty the type of cavitation phenomena which has proved erosive.

Thus far, Lloyd's Register has performed work primarily on ship's rudders and propellers. However, this technique can easily be applied to other industrial equipment suffering from cavitation erosion such as turbines, pumps and waterjets.

As further full scale work is performed, and the techniques adapted for model scale testing, it is anticipated that better ship-model-CFD correlations will be obtained and improved design guidance delivered to propeller and rudder designers.

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