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Understanding Details of Cavitation

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ABSTRACT

Cavitation is a significant problem for the shipping industry as it can lead to ship vibration and erosion, both resulting in increased maintenance costs. Therefore, a better understanding of cavitation and an accurate prediction capability are important.

Lloyd's Register has performed cavitation observations and measurements at ship scale and, from that, has developed a better understanding of cavitation and its effects, which are discussed in this paper. These observations showed that details of the cavitating flow are paramount for the erosive potential of the flow. Furthermore, recommendations on how to avoid cavitation damage are given.

The paper also discusses the improvements of cavitation prediction with computational fluid dynamics (CFD). Unlike more traditional computation methods, CFD has the ability to predict small scale features in the flow, which are important for determining the erosive potential of both sheet and vortex cavitation.

Keywords

Propeller, Cavitation, Observations, Erosion, CFD.

1 INTRODUCTION

As a class society, Lloyd's Register is committed to the structural integrity and safety of ships and to assisting owners and operators to improve the reliability of their ships. Prolonged ship vibration or erosion, both often a result of cavitation, can threaten structural integrity and safety, and lead to the failure of components. To help minimise such risks, Lloyd's Register's Technical Investigation Department (TID) has analysed and researched cavitation on propellers, rudders and other appendages for over 30 years.

Until recently, the analysis of propeller cavitation relied heavily on ship wakefields measured at model scale, corrected for interaction and scale effects, and on lifting surface codes to compute cavitation characteristics. The inaccuracies of this approach and the resulting problems were discussed by Whitworth et al (2008) and a more accurate method using CFD (Computational Fluid Dynamics) was proposed.

The lifting surface codes were quite capable of predicting the overall propeller cavitation development but had problems, in particular, with smaller scale cavitation developments and the prediction of tip flows as illustrated in **Figure 1**. This resulted in erroneous hull pressure predictions.

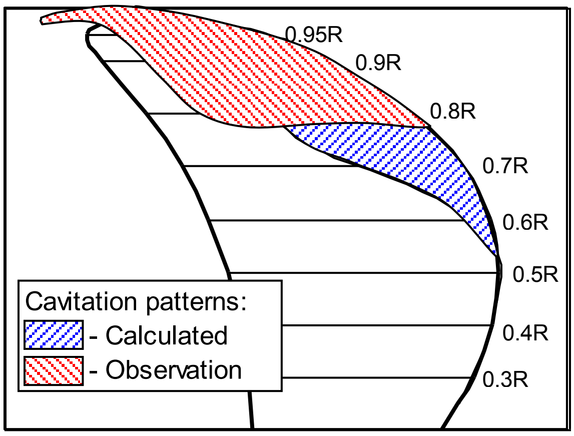

Figure 1: Prediction of cavitation on an LNG ship propeller: calculation with lifting surface method vs. experience

The more recent introduction of Boundary Element Codes such as PROCAL (Vaz 2006) has significantly improved the prediction of flow near the propeller tip although no tip vortex models are currently available. Moreover, the rapid collapse of cavitation, which is often observed at ship scale, is not accurately predicted, possibly a consequence of shortcomings in the physical modelling of cavitation. It is often precisely this rapid cavitation collapse that results in large hull pressures.

Apart from shortcomings in predicting hull pressures, none of the described methods has been able to predict the occurrence of cavitation erosion. One explanation for this is that the cavitation models used are not capable of predicting the focused collapse that is required for cavitation to be erosive (Bark et al 2004). Although, methods exist that have been able to predict the circumstance under which pressure side erosion can occur on propellers (Moulijn 2008).

Ship scale observations, combined with acoustic emission measurements of cavitation impact signals (Boorsma et al 2009), have shown that it is often the details of cavitation that lead to erosion damage. Therefore, a better prediction of erosion requires an improved understanding of the details of the flow. As a contribution to this process, an overview of erosion damage and a number of observations of the detailed development of cavitation are presented in the first half of this paper.

In the second half of this paper, the prediction of those cavitation details that can not be computed with the more traditional lifting surface and panel based methods will be discussed. This paper will show that CFD can be utilized to both predict the details of cavitation and provide a qualitative estimate of the erosive potential of a cavitating flow.

2 EROSION

Erosion is not uncommon on ship propellers and appendages. The origins of cavitation erosion, i.e. the type of cavitation, are sometimes clear, especially in the case of rudder erosion. However, erosion can sometimes manifest itself at locations that are less obvious and more specific recommendations might be required.

Figure 2: Cavitation damage on a dredger propeller

Figure 2 shows a set of blades from a dredger propeller with damage in a long streak just behind the leading edge on the pressure side of the propeller. The depth of the damage had reached 3.7mm after 1 year in service. The location and shape of the eroded area suggested erosion occurred during low pitch and high shaft speed conditions. On dredgers, such operating conditions would occur during dredging which would be a considerable part of the service time of the vessel. When operating at low pitch and high shaft speed, a cavitating leading edge vortex can occur on the face of the blade then disintegrate, causing high pressure impacts in the area where erosion is observed. It was recommended to re-design or modify the blades to better suit this condition.

Figure 3 shows a shaft bracket on a small cruise vessel. Paint removal in way of the propeller tips was noted directly after the sea trial and, unusually for cavitation damage, it did not appear to originate from the leading edge of the bracket but instead from the trailing edge. When a second inspection at the 1 year dry docking revealed that damage had not progressed, it was concluded that erosion could have occurred during extreme conditions of the sea trial. This extreme condition was likely a hard astern manoeuvre during which a cavitating vortex from the propeller impinged on the shaft bracket. It was thus recommended to avoid hard astern manoeuvres where possible.

Figure 3: Cavitation damage on an A-bracket

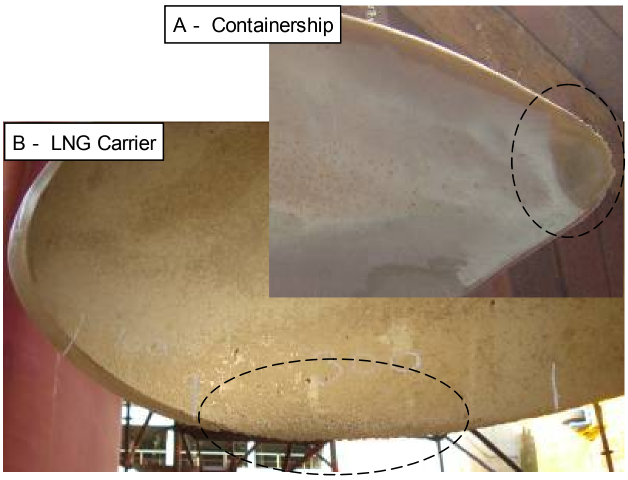

Figure 4: Erosion of the propeller tips

Damage to the 'ear' of a propeller blade of a containership is shown in **Figure 4a**. In most cases, such damage is simply left or, preferably, cut off and the surface redressed. A similar strategy has not been recommended for the damage to the propeller of an LNG carrier in **Figure 4b**, as this occurred after only 1 year in service. In this case, further investigations, such as presented in this paper, might be recommended to determine palliative measures and to improve the design of future hulls and propellers.

3 THE IMPORTANCE OF CAVITATION DETAILS

The flow around ships, propellers and appendages is the result of complex interactions. The details of such interactions are not often clear and are extremely difficult to predict. High speed video observations of cavitation are therefore an excellent aid to visualize and help understand flow features. Two such detailed observations of the flow will be discussed. The first concerns the interaction of a tip vortex and the leading edge of a rudder. This flow often leads to rudder erosion. The second example shows how the complex interaction of the flow around a propeller can lead to erosion and suggests ways in which this can be avoided.

3.1 Vortex - Rudder Interaction

Erosion damage to the rudder leading edge is often a result of repeated impacts from the cavitating propeller-tip vortex streaming aft. **Figure 5** shows a detailed observation of the impact of a cavitating vortex on a rudder. This was recorded on a cruise vessel at 540 frames per second with a dedicated borescope observation system (Fitzsimmons et al 2007).

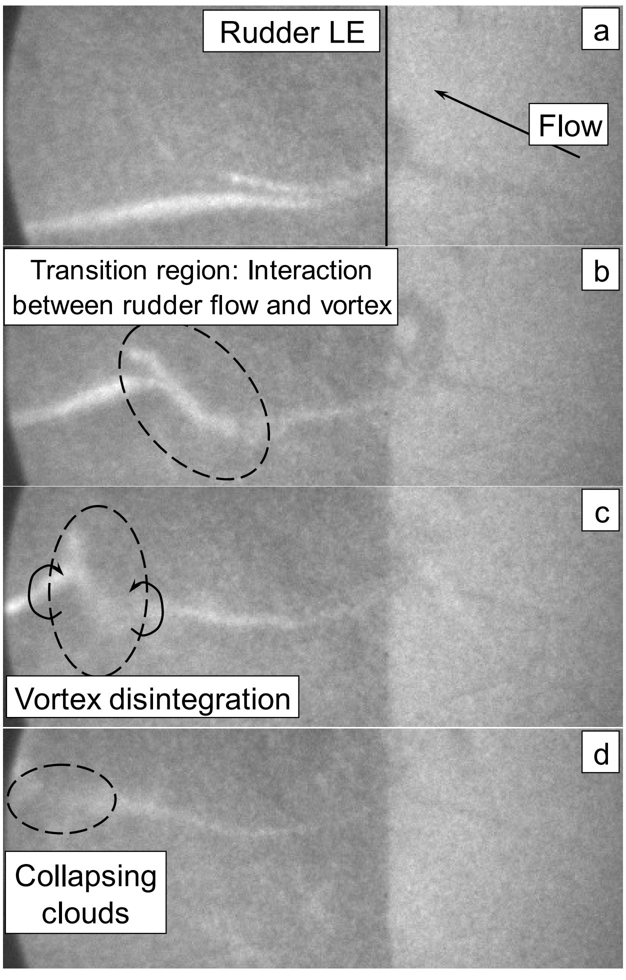

Figure 5: Vortex – rudder interaction.

Figure 5a shows how the vortex impinges on the rudder leading edge and a secondary cavitating vortex is created just above the original cavitating vortex. This secondary vortex has been observed on other vessels, though its origins are not quite clear. Since the secondary vortex is not visible while the primary vortex approaches the rudder, it is likely that the secondary vortex is created, or amplified, by the interaction with the rudder. It might be that, as result of the interaction of the vortex and the rudder boundary layer, a counter rotating vortex is created and sustained by the on-going interaction.

While the primary vortex in the free flow moves further aft, the portion ahead of the rudder is held back as shown in **Figure 5b**. This deforms the cavitating vortex in the transition region where an interaction with the secondary vortex is visible.

The vortex in this transition region then disintegrates in the area where, typically, erosion can be observed, **Figure 5c.** The remaining vortex at the rudder leading edge appears to reduce in strength (i.e. the integration of vorticity over the cross-section of the vortex) without disintegrating which might also explain why the secondary vortex disappears in this region. The disintegration of the vortex in the transition region might be the result of the interaction between the primary vortex in the free flow and the vortex at the rudder leading edge which, in this region, are orientated at a 90 degree angle. Therefore, they result in flows in opposing directions in the transition region near to the rudder surface. This could destroy the weakest vortex, i.e. the one in the transition region. This might then lead to erosion.

Figure 5d shows how the remains of the disintegrated cavity flow further aft, possibly leading to repeated cavitation impacts as the cavity rebounds. Simultaneously, the vortex at the rudder leading edge gradually reduces in strength without leading to an erosive collapse of the vortex cavitation.

It must be noted that the observations in **Figure 5** have been taken on the pressure side of the rudder. Fitzsimmons (2009) has described how the erosive potential of the interaction between a cavitating vortex and the rudder leading edge is greatly increased by a suction peak on the rudder. This suction peak is generated by the inflow angle of the propeller induced transverse velocities. In the case of the rudder in **Figure 5**, this suction peak is on the inward facing side. Looking at the images in **Figure 5b** and **5c** it is not difficult to imagine how the impact strength of the imploding cavity might be increased by a temporary increase in the cavity volume of the disintegrating cavity. Such a scenario could occur as the cavity passes through the suction peak on the rudder, thus allowing more energy to be released by its implosion onto the rudder surface.

From this and other observations it can therefore be concluded that both the strengths of the tip vortex and the suction peak at the rudder leading edge are important factors in determining whether rudder erosion will occur. To avoid rudder erosion it is therefore recommended to:

- Reduce the propeller-tip vortex strength by reducing the propeller tip loading.
- Increase the distance between the rudder and propeller to reduce the transverse velocities at the rudder leading edge.
- Twist the leading edge of the rudder to reduce the suction peak on the rudder leading edge.

3.2 Propeller Cavitation Details

The determination of the erosive potential from cavitation observations has been discussed by Bark et al (2004). Boorsma et al (2009) added more information by quantifying the cavitation impact using acoustic emissions and showed how relatively small features of propeller cavitation can lead to erosion. **Figure 6** shows the development of such minor features of cavitation.

Images A1 to D1 in **Figure 6** show cavitation recorded on tanker 1 and have been discussed previously by Boorsma et al (2009). They show how the development of a separate cloud of cavitation (image B1) gave rise to a large impact on the propeller tip. The area where this cavity was seen to collapse coincided with the area where erosion was observed.

Images A2 to D2 in **Figure 6** were recorded on a different tanker, designated tanker 2, where no erosion was noted. However, they clearly illustrate how the separate cloud of cavitation is generated.

Images A1 and A2 show how the residual cavitation clouds, a result of the cavity collapse behind or on the previous blade, linger in the wake peak, possibly exacerbated by the vortex flow emanating from the propeller tip.

As a new blade moves into the wake peak, image B1 shows how a separate cloud of cavitation is formed on the propeller of Tanker 1. Image B2 shows how a separate streak of cavitation is formed at this location on the propeller of Tanker 2. This separate structure of cavitation develops further, as shown in images C1 and C2, as a result of the interaction between the flow around the blade in the wake peak and the preceding blade. The cavitation is possibly boosted by the presence of nuclei in the flow, a result of remnants of the cavitation on the previous blade moving to the current blade via the tip vortex.

Images D1 and D2 show the collapse of this separate streak of cavitation: on the blade on Tanker 1 (image D1), leading to erosion, and off blade on Tanker 2 (image D2), not giving rise to erosion.

Hence, the development of such types of erosive cavitation is a result of interaction of the flow around two consecutive propeller blades. This interaction is only possible because a combination of slow propeller inflow in the ship wake and the flow around the tip vortex are creating a local region of very slow flow, leading to a separate cloud of erosive cavitation. Therefore, this type of erosion can be avoided by:

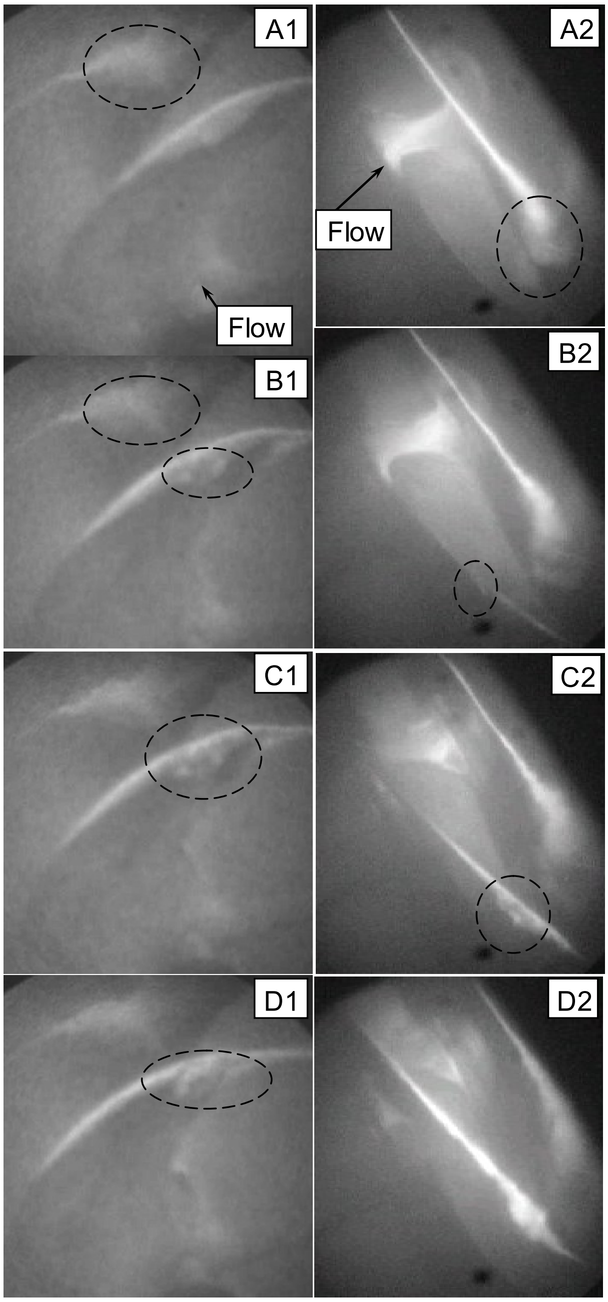

Figure 6: Development of erosive cavitation on a propeller. A1 to D1 on Tanker 1, A2 to D2 on Tanker 2

- Improving the wakefield by changing the hull lines and/or fitting flow improvement devices. Indeed, in the case of Tanker 1, a vortex generator was installed which eliminated propeller erosion.
- Reducing the vortex strength by off loading the propeller tip.

4 THE PREDICTION OF CAVITATION DETAILS

Cavitation around ship propellers is both complex and varied, and the details of the underlying flows are not always fully understood. Accurate CFD calculations offer a great opportunity to help create insight into the flow details for comparison with high speed video observations and acoustic emissions measurements. At the same time, the lack of understanding makes simulation of these processes a considerable challenge.

Most of the cavitation analysis capabilities of today's CFD codes incorporate a degree of empiricism that can make accurate modelling almost as much an art as a science. This is further complicated by the presence of very small time and length scales which are inherently hard to model for typical ship dimensions.

The main types of cavitation on propellers are sheet and vortex cavitation; however, the range of cavitation models commonly employed in CFD codes are not formulated with such problems in mind. Most are based on a simplified version of the Rayleigh-Plesset equation, which describes the growth and collapse of a spherical bubble, and, for simplicity of implementation, opt to neglect higher order terms. Whether these models can, or should, be routinely applied to more complex cavitation problems is a point of some debate, the details of which will not be discussed here. However, the following examples will show that their careful application can yield interesting and reasonably accurate results.

Accurate turbulence modelling also becomes much more important in order to better capture local flow features affecting cavitation. Standard turbulence models based on Reynolds Averaging (RANS) are often too limited by the in-built assumptions to achieve the necessary resolution of the flow features. On the heels of huge advances in computer hardware, more advanced turbulence models have been coming to the fore, such as Large Eddy Simulations (LES) and Detached Eddy Simulations (DES). These dynamic models are capable of capturing much smaller length scales and are better suited for cavitation modelling.

4.1 Propeller Cavitation Prediction

The first example is from a liquefied natural gas carrier that experienced vibration problems attributed to propeller - hull pressure excitation. Observations of the cavitation patterns and measurements of the vibrations were performed onboard the ship. Unfortunately, poor water quality during the observations meant that visibility around the propeller was low and the resulting propeller cavitation observations did not show the details of the flow with the level of clarity that would be desirable. Despite this, the major patterns of the cavitation could be deduced and were confirmed to be very similar to those observed in cavitation tunnel tests.

The cavitation around the propeller of the LNG carrier was simulated using the commercial solver STAR-CCM+ with an additional modification to the cavitation model that aims to promote cavitation growth in the core of the tip vortex. Despite recent advances in computing power, resolving the tip vortex in a CFD simulation is usually impractical to achieve due to the very small diameter of the core of the vortex in which the pressure is predicted to be low enough for cavitation to be generated. **Figure 7** compares the model scale cavitation tunnel observations with the ship scale CFD predictions.

In **Figure 7**, a sheet cavity grows from the leading edge of the blade as the propeller traverses the wake peak. As the blade passes out of the wake peak much of the on-blade sheet cavitation collapses. However, a significant volume of cavitation survives off the blade. This interacts with the tip vortex before also collapsing.

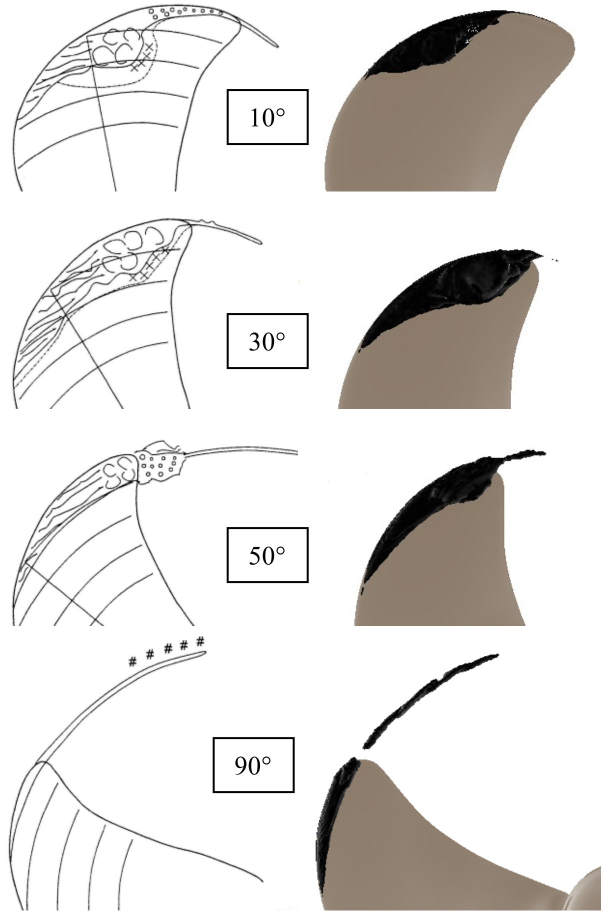

Figure 7: Growth and collapse of cavitation on and around the propeller of the LNG carrier from cavitation tunnel tests (left) and CFD analysis

4.2 Methods for Cavitation Erosion Prediction

Whilst most CFD codes commonly used in the marine industry incorporate models for cavitation modelling, models for the prediction of cavitation erosion are scarce, possibly owing to the limited understanding of cavitation erosion and the small time scales involved in the events. Given this, and the importance of the problem, Lloyd's Register has been researching techniques for erosion prediction with a view to developing a suitable erosion model based on information obtainable from a cavitation analysis.

An essential prerequisite for cavitation erosion prediction is to ensure that the cavitation patterns are predicted accurately and in detail. For simple laboratory test cases, this is certainly achievable, as the comparison below of the experiment of Escaler et al (2001) with the calculated cavitation pattern of Radosavljevic & Whitworth (2010) demonstrates (**Figure 8**). This simulation was performed through the application of a DES turbulence model, a mesh size of less than 0.5mm in the crucial areas and a time step of 10µs.

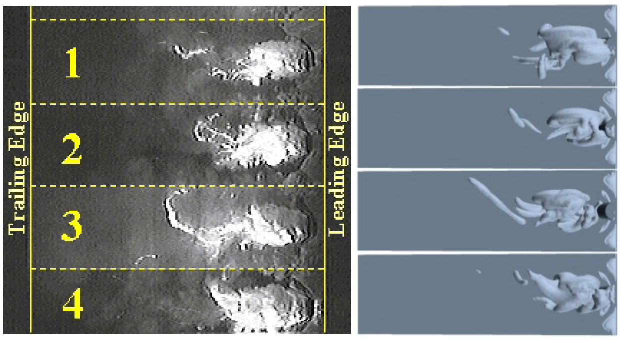

Figure 8: Comparison of cavitating flow from experiment (left) and computation

The analysis was only run for a physical time of 80ms (at a cost of 1400 CPU hours) but, whilst the flow was highly irregular, the initial large variations in cavitation volume and wall pressures settled down after ~20ms into semi-regular oscillations with periods between 10ms and 20ms.

One method commonly employed to estimate the erosive potential of a cavitating flow is to simply look at the maximum pressure on the surface due to cavitation collapse events over a period of time (e.g., Schmidt, S. J. et al 2008). However, in many cases, the best that can be achieved using this method is an understanding of where the worst regions of erosion are likely to be. This is demonstrated by **Figure 9**, which shows the erosion pattern resulting from the cavitation in **Figure 8** on four samples of different material alongside the calculated maximum pressure "footprint".

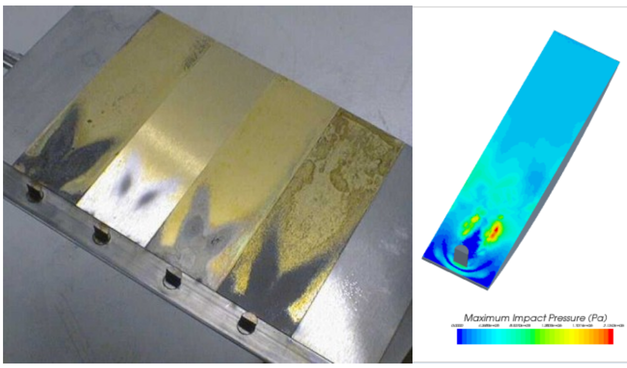

Figure 9: Comparison of experimentally-determined erosion pattern (left) and calculated maximum pressure footprint

The failure of the maximum pressure footprint to predict the distinctive "Y-shaped" erosion pattern is unlikely to be due to inaccurate prediction of the cavitation, as excellent agreement between the predicted cavitating flow and the experimental observations has already demonstrated (**Figure 8**).

Instead, a more accurate description of the erosive potential of the flow was required, based on the understanding that cavitation is most likely to be erosive when the cavity collapse accelerates rapidly towards the surface (Franc & Michel 2004). Various iterations around this theme were explored, two of which are shown in **Figure 10**. When compared to the experimentally-determined erosion pattern in **Figure 9**, it is clear that the erosive potential functions provide a far more accurate prediction of the locations susceptible to erosion than the simple pressure footprint method.

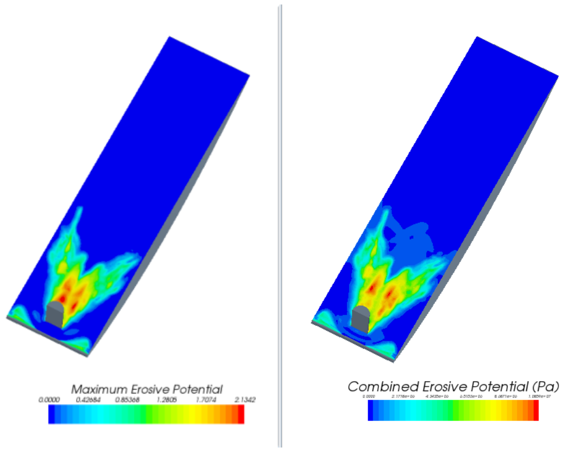

Figure 10: Comparison of two variations of calculated erosive potential

The fine resolution obtained in this case, both spatially and temporally, enables the details of the cavity collapse process to be examined. **Figures 11** and **12** show snapshots taken at three time instances as a cavity collapses towards the surface over a period of 20µs. In the first frame, the ovular cavity is roughly 3mm long and 1mm wide and is collapsing towards the surface with the effect of increasing the potential for erosion. By the second frame, the cavity has almost completely collapsed, implying a rate of collapse of over 300m/s. The collapse appears to be driven by the vortical flow around the cavity. The region of high erosive potential generated by the final collapse is just under 1mm wide and the erosive potential is much more intense than in the first frame. By the third frame, the collapse event is over and the erosive potential of the flow has reduced almost back to normal levels.

4.3 Rudder Cavitation and Erosion Prediction

Rudders can suffer from cavitation erosion problems resulting from two sources: cavitation in the tip and hub vortices originating from the propeller, and cavitation generated on and around the rudder itself. The example presented here is a particularly severe case of the latter, in which the rapid rate of erosion meant that rudder structural collapse could potentially have occurred in less than the intended 3-year docking period of the vessel. CFD analyses of the cavitating flow around the rudder were performed for the two rudder angles that generated the most severe cavitation in earlier tunnel tests. The measure of erosive potential previously validated on simple laboratory cases was applied.

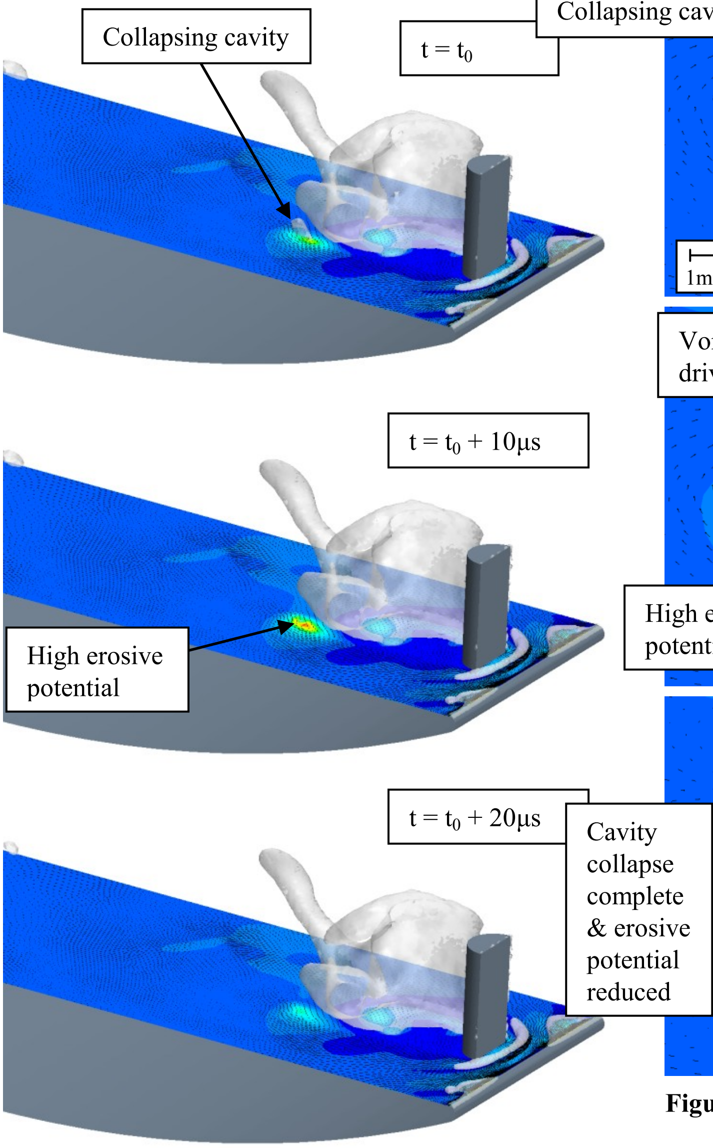

Figure 11: Cavity collapse on the surface of the foil

As with any prediction of cavitation erosion, a crucial first step is to ensure that the cavitation is predicted accurately. While no ship scale cavitation observations were performed for this rudder, the comparison of the predicted cavitation extents agrees well with that observed in cavitation tunnel tests (**Figure 13**) for the two rudder angles considered. This is despite the analysis being performed on a fairly coarse mesh of only 1.2 million cells and using a RANS turbulence model, in this case the k-ω SST model. The problem was solved as an unsteady analysis, though the final result was a predominantly stable cavitation pattern.

Inspection of the rudder identified five key areas in which erosion occurred. Three of these are shown in **Figures 14, 15** and **16** alongside the predictions of the erosive potential of the flow from the CFD analysis.

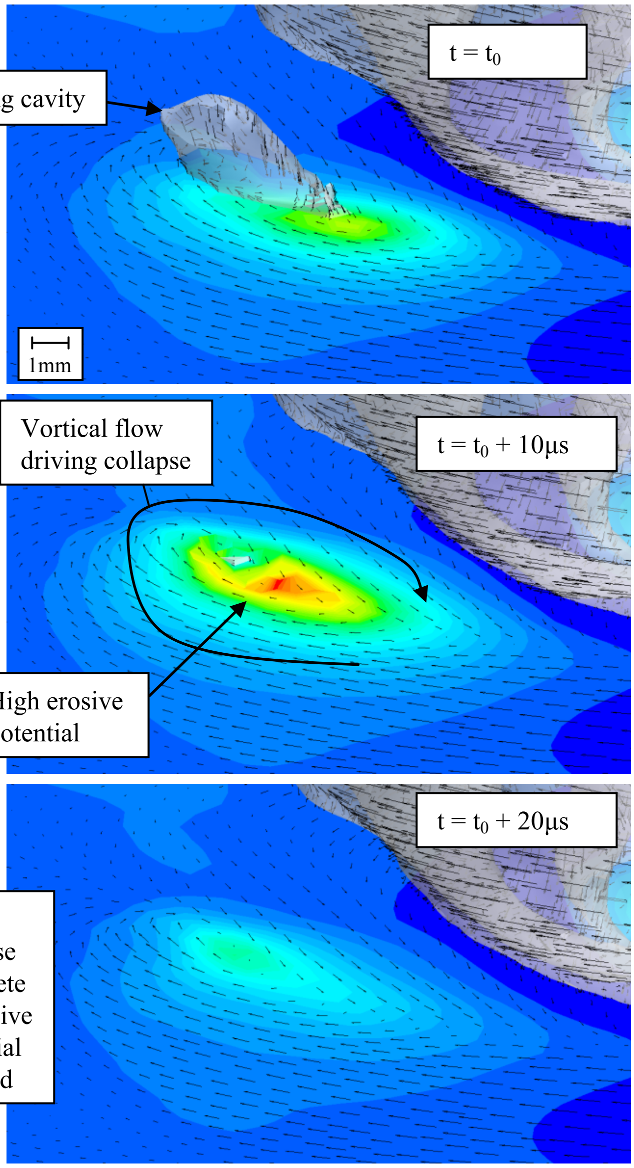

Figure 12: Details of the cavity collapse

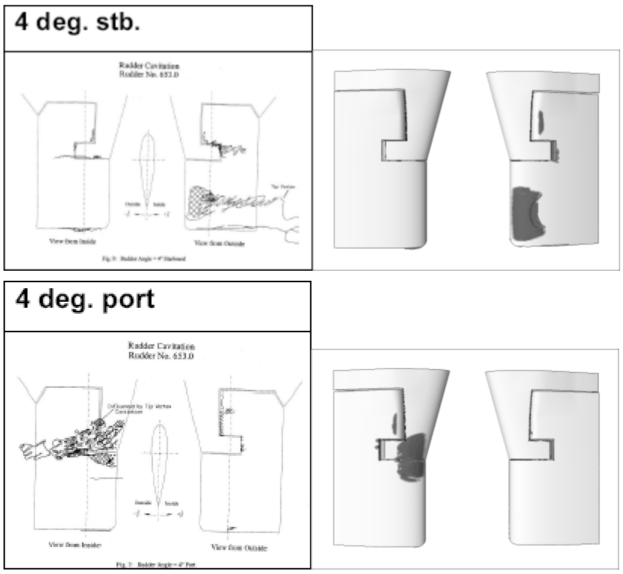

Figure 13: Cavitation pattern around rudder from cavitation tunnel tests (left) and CFD analysis

Figure 14 shows erosion on the side of the rudder blade. Erosive potential is predicted to be very high in this general location when the rudder is turned 4° to starboard. However, the precise pattern of erosion is not fully matched. The flow is not predicted to have erosive potential when the rudder is turned 4° to port.

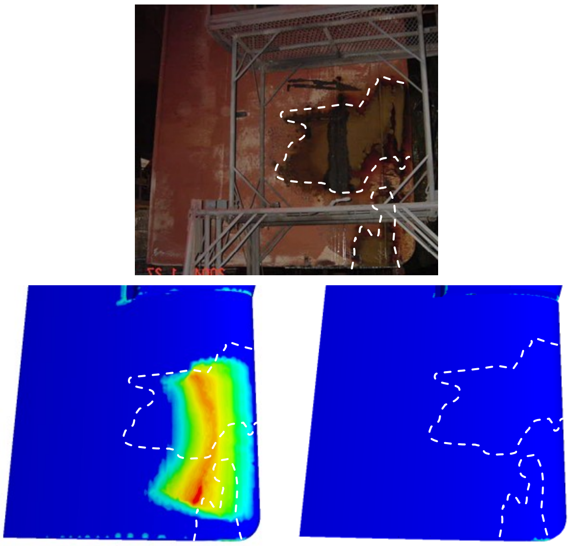

Figure 14: Cavitation erosion on side of rudder blade (top) and predicted erosive potential as calculated when rudder is turned 4° to starboard (left) and 4° to port (right)

The simulations also indicate that the erosion damage observed near the leading edge of the rudder horn, as shown in **Figure 15**, is likely to have occurred while the rudder is turned to port. Again, the erosive potential is predicted to be high in the region where erosion was observed, but the details of the erosion pattern are similarly not fully aligned.

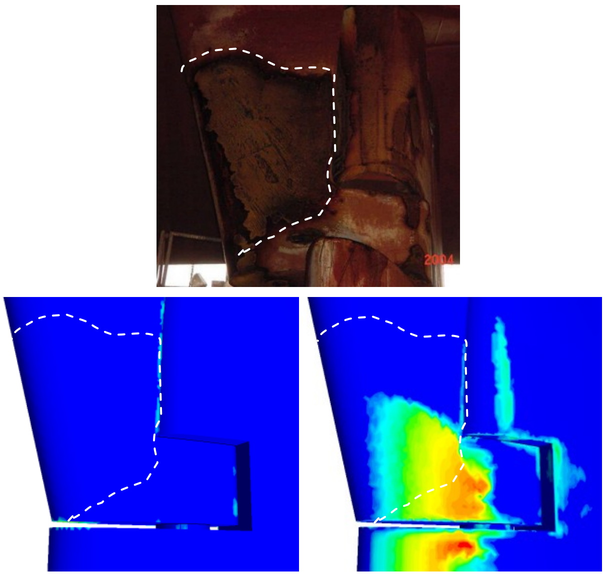

Figure 15: Cavitation erosion near leading edge of rudder horn (top) and predicted erosive potential as calculated when rudder is turned 4° to starboard (left) and 4° to port (right)

Erosion damage around the rudder gap is shown in **Figure 16**. This occurs both forward of the gap, on the rudder horn, and aft of the gap, on the rudder blade. The predictions of erosive potential indicate that the former is likely to be predominantly generated when the rudder is turned to port and the latter when it is turned to starboard.

Figure 16: Cavitation erosion around gap between rudder and horn (top) and predicted erosive potential of flow as calculated when rudder is turned 4° to starboard (left) and 4° to port (right)

Overall, the predictions of erosive potential provide a good indication of the regions of the rudder in which erosion is likely to take place. However the details of the observed erosion patterns are not fully captured in this particular example. There are considered to be two possible reasons for this. Firstly, it is impossible to know under which operating conditions the observed rudder erosion occurred. These analyses were performed at the design speed and at only two rudder angles yet it is probable that cavitation erosion occurs across a range of speeds and rudder angles. Secondly, by employing a relatively coarse mesh and a RANS turbulence model, these simulations could not be expected to predict the small-scale dynamic flow features that were captured in the laboratory test case and which are known to be important in determining whether a cavitating flow is erosive. It is the intention of the authors to repeat these simulations using a finer mesh and a DES turbulence model to assess the possible benefits of adopting a more detailed approach.

5 CONCLUSIONS

This paper has shown how cavitation damage can manifest itself and has explained some of the flow phenomena that can give rise to damage. From this it has become clear that, in particular, the strength of the propeller tip vortex is paramount, and that, in order to avoid damage, its strength should be minimized where practicable.

Furthermore, this paper has shown that CFD calculations, even with the cavitation models currently available, can provide insight into the details of cavitation phenomena, particularly when dynamic turbulence models are employed. Examples demonstrating the prediction of cavitation erosion have been presented and it has been shown that such analyses can be practical for real ship cavitation problems.

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