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Propeller Ice Interaction – Effect of Blockage Proximity

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ABSTRACT
The development of the new generation of podded ice capable vessels have benefited enormously from experimental and full-scale hydrodynamic ice research. However despite the broad international research performed on this topic only a small part of the effort has been applied to the modelling of cavitation during propeller ice interaction. Whilst ice tanks model the contact forces with good agreement, the level and influence of cavitation during propeller ice interaction is often only assumed due to the inability to scale atmospheric pressure during these experiments. Despite a pressing need for information on the influence of cavitation during propeller ice interaction, no in-depth, definitive, propeller ice interaction study exists. This paper reports on tests performed in the Emerson Cavitation Tunnel examining effect of performance of a podded ice class propulsor operating in variable proximity to an ice blockage, a common occurrence during ice transit of podded icebreakers. The findings reported herein are part of a PhD study into the phenomenon.

Keywords
Propeller, ice, blockage, cavitation, podded drive.

1 INTRODUCTION

The design and construction of ice capable vessels is currently undergoing rapid expansion. At the forefront of this boom are the ice-capable Double Acting Ships (DAS) outfitted with podded drives, as reported by **Sasaki et al (2004)**. The DAS concept is innovative, it allows vessels to advance through level ice up to 1.5m thick as shown in Figure 1 at a relatively even speed of up to 3 knots. This continuous advance minimises propulsor ice damage by avoiding the usual "back and ram" manoeuvre conventional shaft driven icebreakers must perform. However the podded drive operates in a low-pressure wake of ice covered flow, which increases the likelihood of cavitation during ice blockage and ice milling. To mitigate against these extremely complex design conditions of low-pressure ice interaction, designers rely on physical model testing to make better informed design decisions. However ice research increases the complexity of contemporary hydrodynamic research and is often only resolved with costly and complex full-scale ice trials. Whilst ice tanks model a more representative ice cover scenario suitable for resistance and self-propulsion tests, they cannot accurately scale the static pressure at the shaft line and this remains one of the numerous assumptions associated with model ice tank testing.

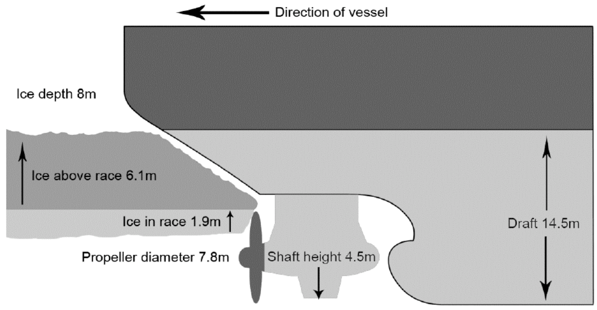

Figure 1. Allocation of depth of cut for the DAS tanker.

Advances continue to be made in model scale research, both in the mechanics of model ice and the ability to measure model scale ice loading more accurately. Despite numerous advances there is still relatively little published work into model scale depressurised propeller ice interaction. One of the first successful attempts at modelling ice blockage phenomenon was **Lindroos (1986)** who used a flat plate to represent an ice blockage and commented on the change in open water efficiency. This work was subsequently advanced by **Shpakoff (1986)** who reported a drop in propeller loading as an ice blockage was moved away from the propeller; one of the first authors to comment on proximity. A more detailed contribution to cavitation during propeller ice interaction was that by **Walker & Bose (1995)** who studied ice blockage phenomenon in a cavitation tunnel for open and ducted propellers. **Lusnik et al (1995)** working on the same project showed that the decrease in blockage proximity gave an increase in K_T and K_Q loading for a propeller. The work supported the findings by **Shih & Zheng (1992)** who numerically modelled the gap effect that was observed when the ice block proximity was reduced. The gap effect was caused by the reduction in inflow velocity to the propeller and resulted in localised accelerated flow over the propeller blades and an increase in performance. **Minchev (1999)** introduced the first depressurised ice tests with artificial ice blocks; the work studied cavitation effects however ice proximity was also included. The work was successful and subsequently expanded by **Atlar (2003)** to study a DAS tanker propulsor. Whilst the proximity effect of an ice-blocked propeller is somewhat of an axiom of cavitation, the effect of cavitation during the proximity phase has never been fully addressed. Useful ice research on podded propulsors does continue such as **Akinturk (2004)** and **Wang (2007)**, however the effect of cavitation remains remiss, a finding which is industry-wide and something that should not be underestimated.

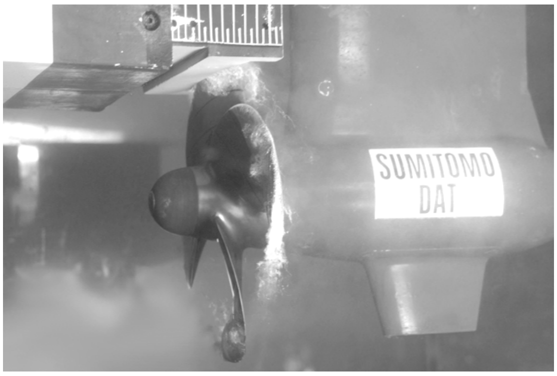

Figure 2. Representative ice blockage test.

To address this lack of knowledge a broad and systematic series of depressurised ice tests have been performed for both ice blockage and ice milling in the Emerson Cavitation Tunnel as shown in Figure 2. This paper reports on an anecdotal series ice blockage tests, which use the proximity effect to highlight the influence of cavitation during propeller ice interaction.

2 IMPLEMENTATION OF EXPERIMENT

The ice interaction tests were performed in the Emerson Cavitation Tunnel (ECT) shown in Figure 3. The ECT is a closed circuit depressurised tunnel located within the University of Newcastle. The basic specifications for the tunnel are given in Table I.

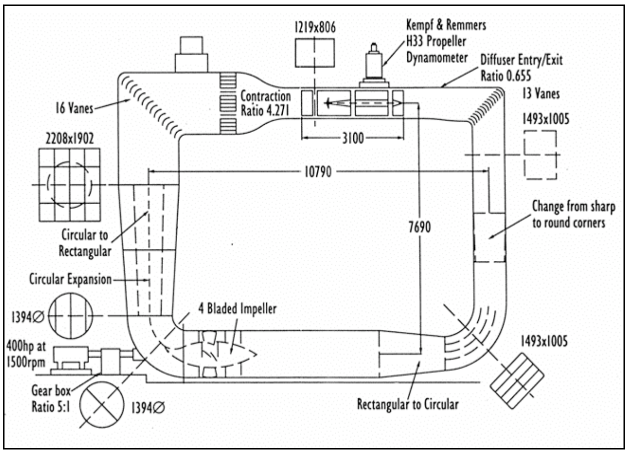

Figure 3: Emerson Cavitation Tunnel schematic.

Table I. Emerson Cavitation Tunnel specification

Tunnel	Emerson Cavitation Tunnel
Facility type	Vertical, closed Circulating
Test section (LxBxH)	3.10m x 1.22m x 0.81m
Contraction ratio	4.271
Drive system	4 Bladed axial flow impeller
Main pump power	300 kW
Impeller diameter	1.4 m
Maximum velocity	8 m/s (15.5 knots)
Abs. pressure range	7.6 kN/m2 to 106 kN/m2
Cavitation number	0.5 (min) to 23 (max)

The ECT has a measuring section of 3.2m x 1.2m x 0.8m; a contraction ratio of 4.274:1 and is therefore considered a medium sized facility. During recent years, numerous improvements to the instrumentation equipment and measuring section have taken place, which increased the capabilities of the facility. In 2008, the tunnel was upgraded with the installation of a new measuring section, guide vanes, honeycomb, quick degassing system and automated control system.

The propeller and pod body used in the experiment was a 1/31.2 scale model of the Sumitomo Heavy Industries (SHI) DAS tanker – a 16MW azimuthing puller type podded drive, fitted with an ice class propeller. The model propulsor was manufactured using CNC, the propeller (P446) was manufactured from hydronalium PA20 and anodized red, whilst the pod body and fin were manufactured in hard plastic and painted to finish. Figure 4 shows propeller P446 used in the test while Table II displays the main particulars of the pod and propeller.

Figure 4: Photo of ice class podded propeller P446.

Table II – Propeller P446 Characteristics

Scale	1/31.2	1/1
Number of blades	4	
Diameter	0.25mm	7.8m
Pitch / diameter at r/R=0.7	0.692	
Blade area ratio	0.540	
Direction of rotation	Right	
Max. pod diameter	106.7mm	3.2m
Strut chord	220.7mm	6.62m
Strut span	131.7mm	3.95m
Max. strut thickness	51.3mm	1.54m

To perform blockage tests in the ECT a substantial test rig was needed to withstand tremendous suction forces whilst providing controllable blockage of the propeller race, Figure 5 shows a schematic of the test rig setup used in the cavitation tunnel; full details of the setup are given in **Sampson et al. (2006)**. The blockage test consisted of a matrix of 12 blocks manufactured from cast resin to simulate systematic changes in levels of ice blockage. The test matrix comprised of 3 block heights, h_i = 0.22R, 0.33R, and 0.40R with 4 depth of recess measured from the propeller tip of d_i = +20mm, 0mm, -20mm, -40mmm. Figure 6 shows the matrix of all of the blockages and Table III the test parameters. For the proximity test only the performance change between the block in front of the propeller (+20mm) and the block flush with the propeller (0mm) were parametrically studied.

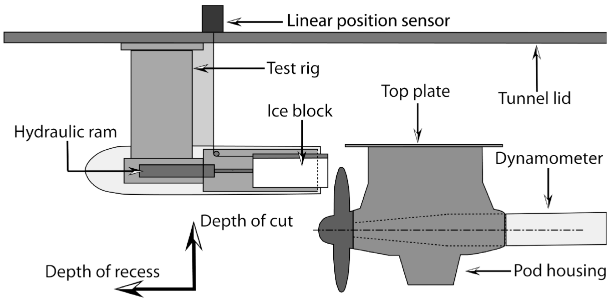

Figure 5: Blockage test rig setup in the ECT

Figure 6: The complete test matrix of cast resin blocks

Table III – Test parameters

Depth of cut (mm)	50, 43, 20
Gap (mm)	+20, +0
Tunnel speed (m/s)	3
Cavitation Number	24, 18, 12, 8

The test blocks were also coded to aid description: A_n = 0.22R, B_n = 0.33R and C_n = 0.40R. The subscript 'n' denoting the axial position n = 0 for the +20mm block and n = 1 for the 0mm block. Finally the test parameters were set using ECT procedures. The air content was held between 25-35%; the model scale Reynolds number gave a value typically $\geq Re = 1 \times 10^6$ and the cavitation number based on the free stream flow velocity (V_x) of the tunnel was selected for practical convenience as shown in Equation 1; performance coefficients are given in Equations 2 – 3 and the Reynolds number in Equation 4.

Cavitation number $$\sigma_v = \frac{p-e}{\frac{1}{2}\rho(V_x)^2} \qquad (1)$$

Thrust coefficient $$K_T = \frac{T}{\rho n^2 D^4} \qquad (2)$$

Torque coefficient $$K_Q = \frac{Q}{\rho n^2 D^5} \qquad (3)$$

Reynolds number $$R_e = \frac{A_E / A_0}{Z} \times \frac{nD^2}{\nu} \qquad (4)$$

3 RESULTS AND DISCUSSION

The results of the blockage test experiment presented in this paper form part of a much wider research programme. The blockage tests provided a quasi-static non-contact analysis of the hydrodynamic loads in the wake of an ice block. A complimentary study followed the blockage tests, which included full-contact ice milling tests. The most important test blocks in the blockage tests were those positioned close to the propeller plane with a small clearance (1.5mm) known as the A_1, B_1, C_1 or ABC_1 blocks. These blocks were significant as key hydrodynamic aspects of the blockage phenomenon such as gap effects were present during the test. This was due to the close proximity of the propeller tip to the block face; this was not always the case with each test block in the matrix. More importantly, the results from blocks ABC_1 were readily comparable to other published data such as **Searle (1999)** and **Walker (1994)**.

It was observed during the experiment that propeller performance varied with the size of the clearance between block and propeller known as proximity. For the majority of the test this was kept constant however with the flat reference block an opportunity arose to study the change in performance due to proximity for 2 fixed conditions. This was a valuable insight ahead of the dynamic milling tests, especially as conventional ice tank tests indicated that the proximity effect was only responsible for an increase in performance due to reduced proximity. As all of the published ice tank work on ice proximity was performed at atmospheric condition, it was not known what the influence of cavitation would have during the tests. Figure 7 shows a schematic of the test blocks used in the experiment, the ABC_0 blocks represented +20mm condition and the ABC_1 blocks the 0mm condition. It is clear from this figure that there was a substantial difference in the block/propeller clearance. Therefore the findings from these 2 series of blocks were used to assess the change in performance due to proximity.

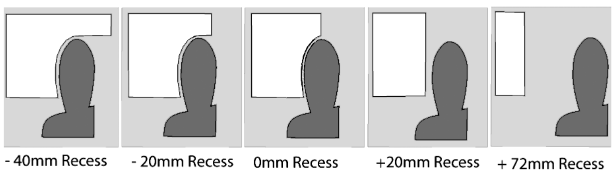

Figure 7. Recess conditions used in the experiment

Prior to the proximity analysis the ABC_0 and the ABC_1 blocks were tested in isolation over a range of cavitation numbers to study the influence of cavitation on performance. Figures 8 ~ 11 show the findings for the individual block series for the C_0 and C_1 series tests. The results in Figures 8 ~ 11 are taken from 6^{th} order polynomial fits of 3 repeat tests. The additional A_n and B_n series tests are not described here as the C_n series tests represented the more extreme and interesting loading scenario. Findings for block C_0 are shown in Figures 8 & 9 for K_T and $10K_Q$ respectively. The 20mm tip clearance from the block increased the performance above the open water condition for all of the curves presented. For the K_T plots shown in

Figure 8 the performance did not change between different cavitation numbers from J = 0.85 until J = 0.55 apart from the lowest cavitation number which experienced a significant offset for the duration of the test. This offset was a function of the lower cavitation numbers in both blockage and milling and was attributed to the large level of cavitation present on the blade for the entire test. With a reduction in J the performance was sequentially degraded with reduced cavitation number analogous to conventional propeller testing. For the $10K_Q$ plot shown in Figure 9 the effect was similar, however all of the curves in this figure were more closely aligned until the cavitation began to developed at low J.

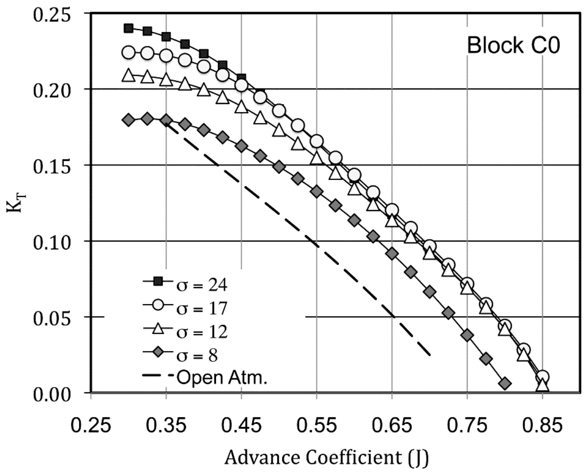

Figure 8. Comparative K_T plot against σ_v for Block C_0

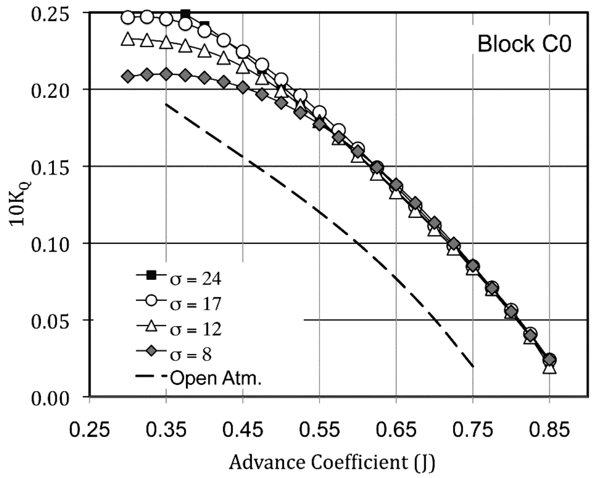

Figure 9. Comparative $10K_Q$ plot against σ_v for Block C_0

Figures 10 & 11 show the results for block C_1 for a similar test condition. The curves in these figures show an increase in performance over the previous C_0 condition however both K_T and $10K_Q$ begin the separate and decline from the start of the test at J = 0.85. For the σ_v = 24 condition in particular, the performance increased with reduced J until at J = 0.55 the cavitation caused a sharp reduction in performance. This effect became less prevalent with a reduction in cavitation number as the level of cavitation present on the blades increased thereby limiting the performance gains possible. For the range of advance coefficients examined in Figures 8 ~ 11, the performance increase was proportional to the level of blockage. The increase was due to proximity/gap effect of a propeller operating close to a solid boundary as described by **Shih & Zheng (1993)** and was bound by the level of cavitation present. **Lindroos & Bjorkstam (1986)** and **Walker (1994)** both noted that changes in advance coefficient had little effect on the performance coefficients when the propeller was heavily loaded. The current work supports this and suggests that the results are less dependent on J than those in uniform flow with many of the curves requiring substantial increases in rpm to change the thrust or torque values. The effect of cavitation in blockage, was to remove the sensitivity towards depth of cut from performance at heavily loaded conditions.

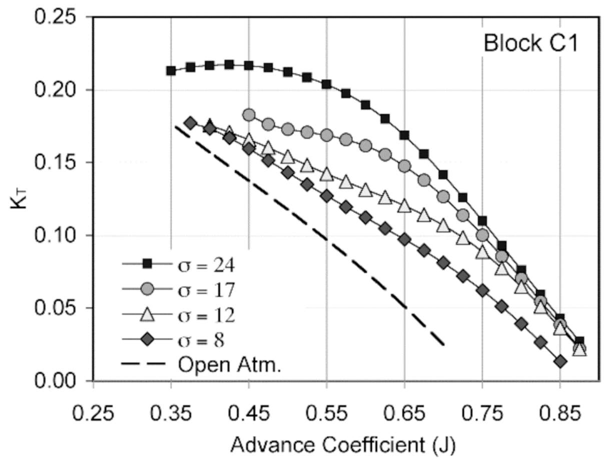

Figure 10. K_T for Block C_1

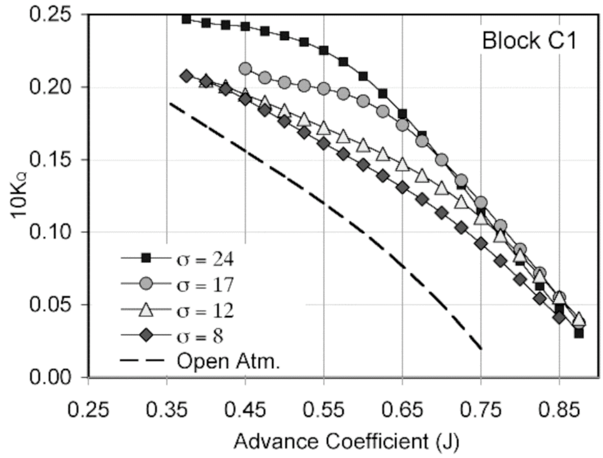

Figure 11. $10K_Q$ for Block C_1

Based on the above findings the difference in performance between the 2 conditions (C_1-C_0) was calculated and the results plotted. Figure 12 shows the results for proximity against changes in depth of cut and Figure 13 shows the results for changes in cavitation number.

Figure 12 gives the results for δK_T, at 3 depths of cut and 4 cavitation numbers (σ_v). Analysis of the curves for the C_n blocks reveal that at σ_v = 24, there was a maximum increase in performance at J = 0.65 of δK_T = 0.055.

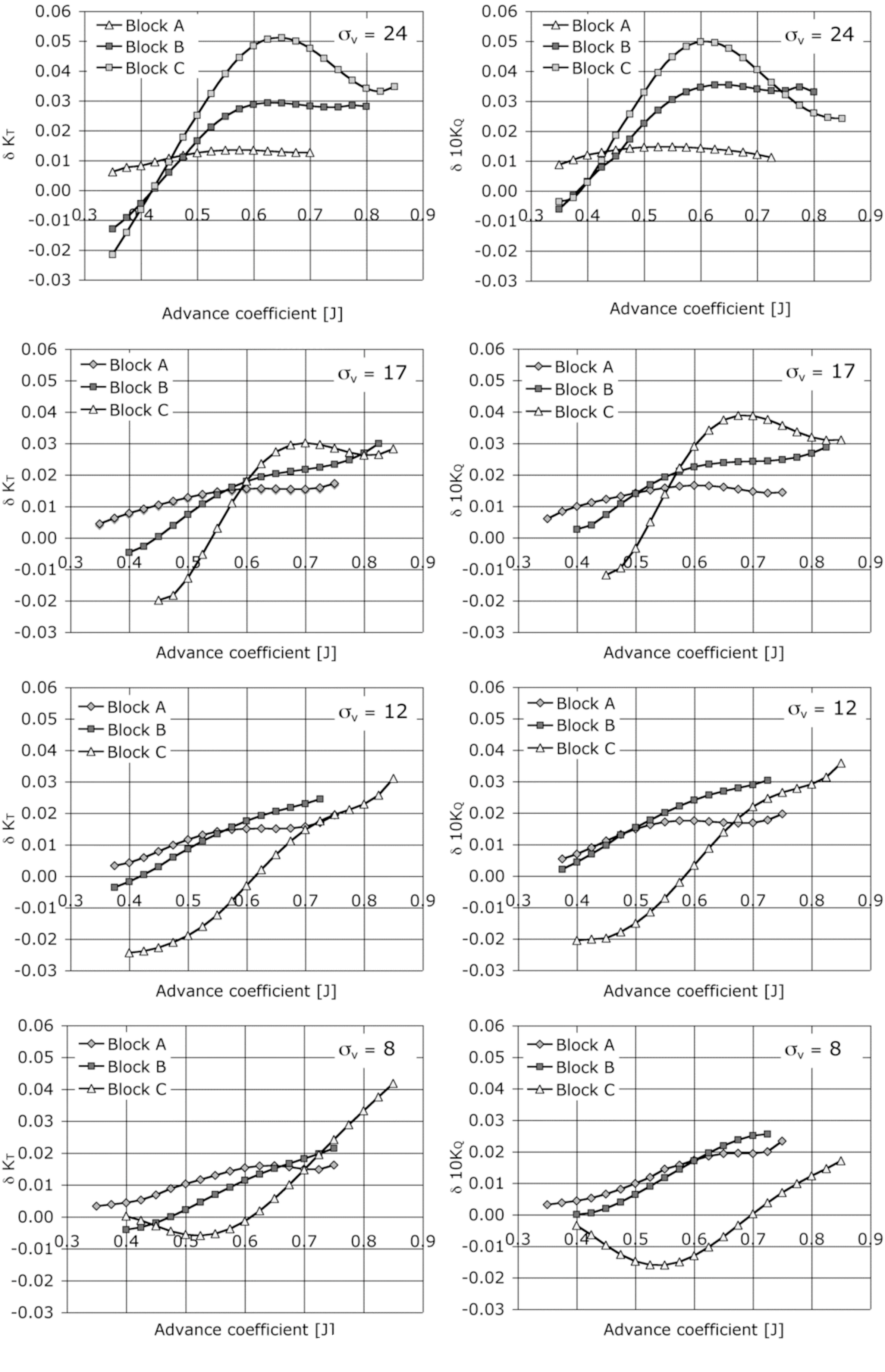

Figure 12. Performance difference (δK_T, δK_Q) due to depth of cut at varying σ_v

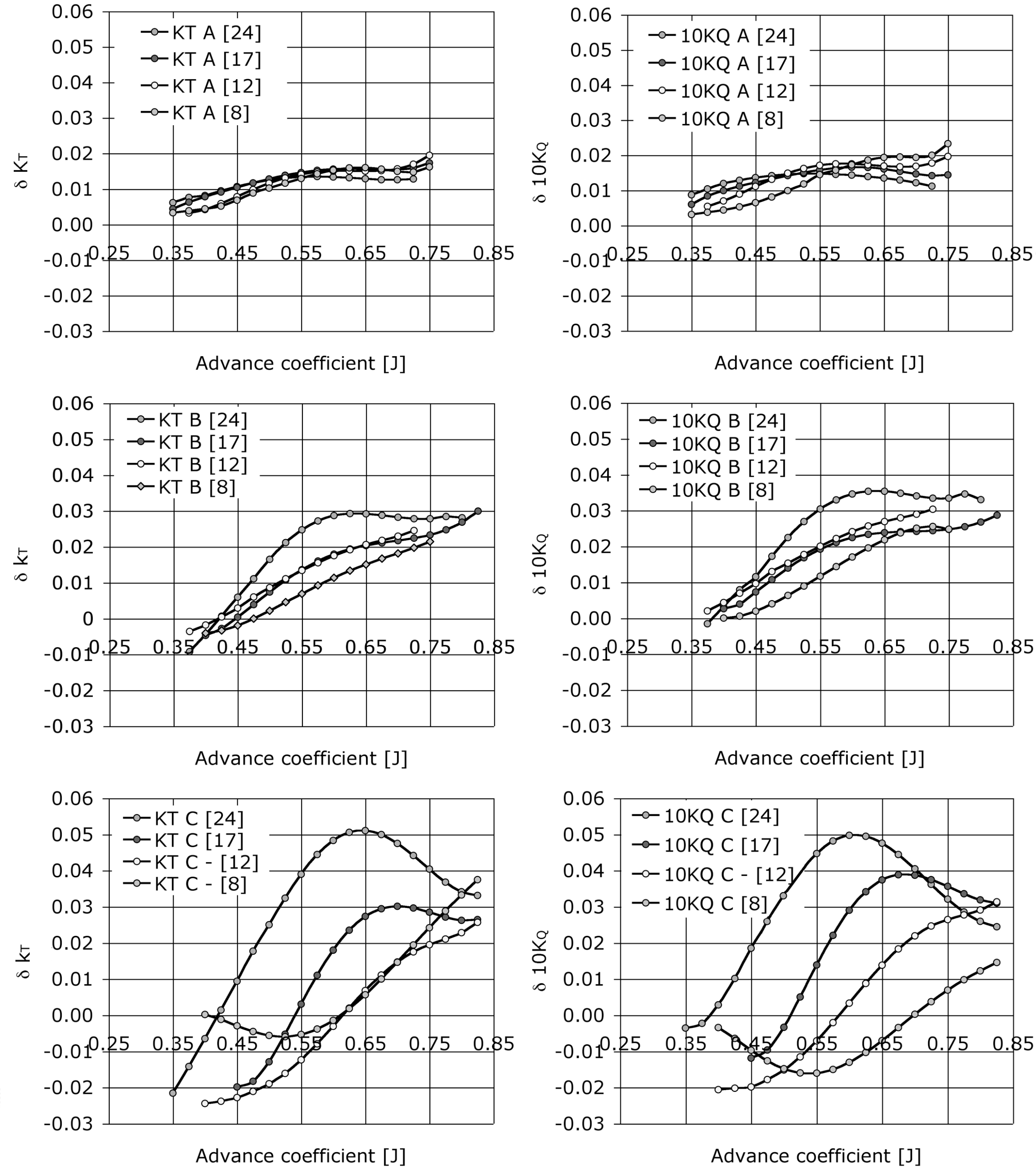

Figure 13. Performance trends in δK_T and δK_Q for changes in cavitation number

A reduction in *J* produced less of an increase in performance due to proximity as the increase in δK_T and δK_Q decayed in a linear fashion until at J = 0.42 the proximity effect was neutral. Beyond this J value there was a loss in performance due to proximity, this was coincident with the excessive levels of cavitation.

For the B_n blocks at $\sigma_v = 24$ in Figure 12 there was less of an increase in δK_T and $\delta 10K_Q$ at high *J*, the curves remained flat and constant suggesting that the increase in performance at this point was not sensitive to a reduction in *J*. The B_n series curves however reached a maximum δK_T at *J* = 0.62 and decayed beyond this with a slightly shallower gradient than the C_n blocks. At the smallest depth of cut the A_n blocks had minimal increase in δK_T and $\delta 10K_Q$ suggesting no influence from the proximity effect and therefore independence from *J*. The decay in δK_T and $\delta 10K_Q$ was not sufficient for either curve to become negative.

Reduction in cavitation number to $\sigma_v = 17$ consistently reduced the performance of all of the blocks, however the C_n blocks showed the most dramatic effect. Initially the performance increased for the C_n blocks until at J = 0.7, the performance began a sharp, uniform decline. With subsequent reductions in the cavitation number the primary hump in the C_n block curves reduced as cavitation modified and reduced the performance at progressively higher J values. At $\sigma_v = 12$ there was a slight hump in the C_n series curve at J = 0.7 however this was not the maximum value and simply a point of inflection in the decline. By σ_v = 8, there was no localised hump in the C_n curve, the effect of proximity was simply a linear reduction in performance for reduction in J. Interestingly at σ_v = 8 the C_n curves show a performance increase between J = 0.55 to J = 0.4; the cause of the performance increase is unknown. However, it is likely to be related to changes in cavitation due to proximity and one blade operating in a fully stalled cavity of the blockage whilst the remaining 3 blades operating in uniform flow. With reference to photographs of the 2 blocks given in Figures 14 & 15 it is clear that the cavitation patterns for block C_0 are significantly less developed than those for block C_1.

Figure 14. Cavitation patterns for C_0, J = 0.35, σ = 12

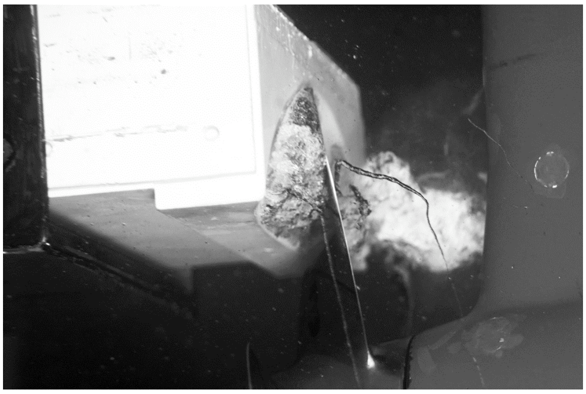

Figure 15. Cavitation patterns for C_1, J = 0.35, σ = 12

The cavitation present on block C_1 would quickly reach a point where the blade operates in a fully developed violent cloud cavity behind the blockage. Therefore the performance contribution to K_T from this blade was effectively removed, it becomes less sensitive to changes in shaft rotation. Conversely block C_0 for the same shaft rotation has just entered into a cavitating regime and begins to experience a reduction in K_T. Finally, the open water load generated by the 3 remaining blades becomes the larger load component. With further increases in rpm and hence reduced *J*, the 3 blades increase their loading density until cavitation once again, reduces their performance. Whilst the small depth of cut may not be a problem at atmospheric condition changes in combination with the cavitation displaying large variations for the highest depth of cut. The influence of cavitation on blades outside of the ice recess on the performance is another aspect of the test, which is not modelled by researchers.

Building on the depth of cut analysis for proximity, Figure 13 extends the study to consider changes in cavitation number. For the A_n series blocks given in Figure 13 (row 1) there was little influence due to either proximity or cavitation. Insufficient cavitation was generated and therefore the thrust and to a lesser extent the torque curves were relatively concurrent. The increase in depth of cut for B_n series blocks (row 2) however shows that depth of cut was sufficient to promote a proximity effect; this was quickly influenced by the cavitation number. The slope for the A_n series was almost horizontal however, for the B_n series the rate of performance loss has increased with the largest gain observed at the atmospheric condition. Finally the C_n series blocks (row 3) showed the greatest gain in performance due to proximity and also the greatest, and most rapid losses from cavitation. For σ_v = 24 and σ_v = 17 the curves for reduction in performance had similar slopes, the cavitation number drastically modified the peak value of each curve. For σ_v = 12 and σ_v = 8 the curves were concurrent.

From the analysis of Figure 13 it is clear that proximity and cavitation are inter-related terms. Blockage loads were elevated by reduced proximity until the gap between the block and the propeller was filled with violent levels of cavitation. Blockage therefore reduced the inflow rate to the propeller causing the affected flow zone to be rapidly accelerated to compensate. The localised increase in acceleration over the blades causes an increase in lift forces and hence performance. If the propeller demand was to great for the blocked flow there were 2 possible outcomes. First if the propeller could not ingest sufficient flow it would draw air from the free surface, this is common in ice tank testing and was observed by **Walker (1997)**. However if there was no free surface such as a cavitation tunnel, ventilation was not possible. Instead the flow would be accelerated until the pressure drops below the vaporisation pressure and the flow will cavitate. The increase in loading would lead to the development of this cavity causing the blade to stall and loose lift in this zone. For the majority of the blockages tested the restricted flow was severe enough to cause this effect to happen. The proximity test has therefore shown that the increase in performance accepted in the wider ice community was more complex than previously thought. Without the ability to model cavitation correctly the performance would simply increase with reduced *J*, little or no performance breakdown would occur. Another author to cover the blockage load was **Luznik (1995)** who also saw that the effect of proximity was to further increase in the performance coefficients, however his work was performed in a towing tank in the absence of cavitation. **Luznik (1995)** concluded that the non-linear relationship between blade to block clearance and thrust and torque mean loads should be considered in class or regulatory bodies; the current results support this. The usefulness of the proximity study was clear when comparing results from the ice blockage test in Figure 16 with a sample from the milling test in Figure 17. The blockage test shown in Figure 16 was constructed from 5 separate blockage tests performed at the same depth of cut but varying depth of recess shown on the figure. The results are given for the same cavitation number and contours of constant *J*. Inspection of the figure shows that between d_i = 20mm and d_i = 0mm there was an increase in performance as the propeller/blockage proximity was reduced to a clearance value of 1.5mm. The performance increase was not constant; it was dependant upon *J* and level of cavitation present. For the J = 0.58 contour indicated with an arrow, there was practically no increase in performance from the presence of the blockage, beyond this point a reduction in J and the presence of the blockage actually caused a reduction in performance, something not mentioned in the open literature.

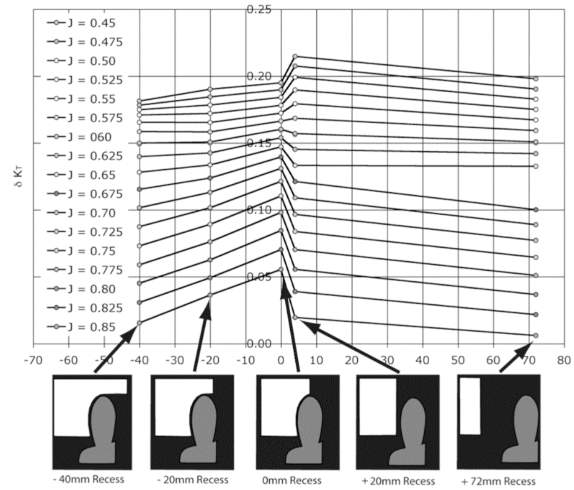

Figure 16. Matrix of blockage test results for proximity.

For the lightly loaded ice milling test shown Figure 17, the effect of reduced proximity was clearly visible as a systematic performance increase towards ice impact at block highlighted with a box. Also shown behind the mean load curves in Figure 17 is the highly unsteady raw time signal. This is a function of cavitation and can incur tremendous oscillatory loading as a result. However, the commonality and synthesis between these 2 phases of the experiment is still ongoing within the ECT.

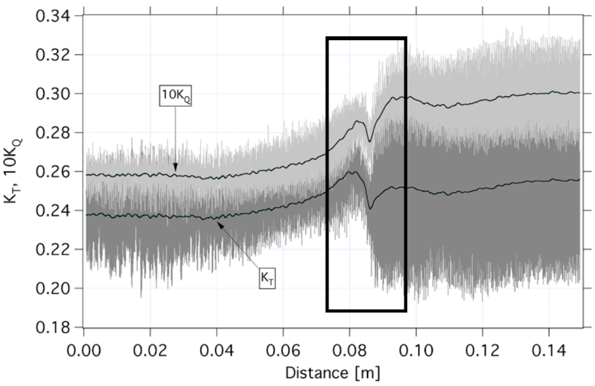

Figure 17. Milling sample showing the impact zone.

4 CONCLUSIONS

A systematic study into propeller ice interaction experiment under depressurised conditions has been performed in the Emerson Cavitation Tunnel. From this study the effect of blockage proximity on the performance of a podded propulsor was studied. The following conclusions were drawn:

- For heavily loaded cases representative of full scale ice breaking the effect of cavitation in blockage caused the change in performance to become insensitive to increases in depth of cut .
- The proximity effect, which is regarded as a performance increase in close proximity of an ice blockage was sensitive to the effect of cavitation. For representative conditions the proximity effect was removed and even contributed to a loss in performance.
- Ice tanks over predict the mean proximity load and any unsteady loading phenomena associated with it as they are unable to model cavitation.
- The effect of cavitation during propeller ice interaction has through an anecdotal example been shown to be significant. Further research into the phenomena is required especially for the new generation of podded ice capable vessels due to their mode of operation.

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