

An Experimental Study into the Effect of Foul Release Coating on the Efficiency, Noise and Cavitation Characteristics of a Propeller

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ABSTRACT

As fuel prices have quadrupled during recent years, the maritime community has looked for effective means of improving the propulsive efficiency of their ships. This has recently been coupled with tougher environmental regulations which have forced the shipping community to review their anti-fouling policies. With the introduction of a new generation of antifouling coatings to satisfy these regulations, it is now possible to apply these coatings not only to keeping the hull free from bio-fouling but also on propellers to improve their performance.

Within the above context a leading research programme, into the effect of the coatings on the hydrodynamic performances of marine propellers, has been underway in Newcastle University together with a major paint manufacturer. This paper reports on the effects of foul release coatings on the efficiency, cavitation and noise characteristics of a marine propeller based on model tests. The paper includes the details of these propeller tests conducted in the Emerson Cavitation Tunnel at Newcastle University and discusses, paint application, surface characterisation issues and analysis of the test results for the coated and un-coated conditions

Keywords

Foul release coatings, propeller model tests, bio-fouling, propeller efficiency, noise, and cavitation.

1 INTRODUCTION

Unpredictable fuel prices and environmental requirements in recent years have forced the maritime community to reduce fuel consumptions of ships by improving their propulsive efficiency. In order to improve the propulsive efficiency of a ship it is important not only keep the hull free from bio-fouling, but also its propeller.

Fouling is the attachment and growth of marine organisms on immersed surfaces. This process occurs naturally and increases the frictional resistance of ships which contributes up to 80-90% of the total resistance for cargo carriers and tankers and more than 50% for high speed craft (Lackenby, 1962). The fouling raises the power requirements of ships and thus their fuel consumptions. Aertssen (1961) reported a 30% increase in the powers of cross-channel ferries with only moderate fouling. Milne

(1990) for example, estimated that the cost saving effect of antifouling on all marine transportation would be about 40% less fuel consumption than that produced without any antifouling being applied.

When the reduction in ship performance is associated with the condition of the ship hull, the effect of the propeller fouling is often overlooked. Nevertheless, the effect can be significant. Mosaad (1986) stated that the effect of the propeller surface condition could be less important than the hull condition, but it would be significantly more important in terms of energy loss per unit area. In economic terms, high return on a relatively cheap investment can be obtained by a properly set propeller maintenance strategy. This has further supported the idea of coating propellers using similar antifouling systems to those used on a ship's hull.

Since ancient times, marine fouling has been mainly combated by chemical methods in combination with various toxic compounds such as; Arsenic, Zinc, Tin and Copper (Anderson et al., 2003). The most effective chemical method to date has been Self Polishing Copolymer (SPC) technology containing Tri Butyl Tin (TBT-SPC). In the 1990's however, it was demonstrated that TBT caused harmful side effects on non-fouling marine life. Therefore, "International Convention on the Control of Harmful Anti Fouling Systems on Ships" (IMO-AFS Convention) was declared by International Maritime Organisation (IMO). This convention has banned the application of TBT paints on newly built ships from 1/1/2003 and the use (or presence) of TBT paints on existing ships from 17/09/2008 (IMO, 2001). The European Commission (Directorate-General for Energy and Transport) also issued a TBT Regulation following the Regulation (EC) No 782/2003 of the European Council and Parliament (EC, 2003). This has led to a new range of more environmentally friendly antifouling systems being introduced to the market.

As an alternative to the above mentioned chemical methods, a new and completely environmentally friendly combating system was introduced in the early 1990's. This new antifouling technology makes use of silicon based, low surface energy coating materials and is known

to be “Foul Release” technology. In this technology the method of fouling control relies on the prevention of a secure attachment of the fouling organisms, allowing them to be removed by hydrodynamic shear forces rather than their eradication once the organisms have settled on the hull. After the introduction of the Foul Release technology, increasing environmental concerns and other reported attractive characteristics (hydrodynamic and application related) of this coating system have resulted in the introduction of different foul release coating types and increased number of applications for ship hulls and propellers.

Within the framework of propeller applications, in order to overcome significant losses in propulsive efficiency resulting from blade roughening due to fouling, an initial experiment by Matsushita and Ogawa (1993) tested a foul release system on the propeller of the training ship ‘Yuge-Maru’. The results showed that a foul release system can protect propellers from fouling for at least one year, but no investigation was conducted into the effect of the coating on the propeller performance. Based on the surface roughness analyses of the foul release coatings and computer simulations, Atlar et al. (2002) and Atlar et al. (2003) showed that these coatings have the equivalent drag of a new or well polished propeller and quantified that the coated propeller can display up to 6% gain in the efficiency against the same propeller without a coating. This highlights the importance of the roughness characteristics affected by the coating on the blades. On the other hand, fouling and roughness are not necessarily the same thing, although both cause drag increases and loss of efficiency. In supporting the above, computer simulations using two sets of full-scale trial data with the Newcastle University research vessel were conducted to investigate the effect of foul release coating applied on its propeller only (Mutton et al., 2005). The trial results indicated no discernable difference in the measured power due to the effect of propeller coating. However, the measured roughness and texture characteristics were incomparably more favourable for the coated propeller and remained almost similar over three years whilst the propeller was free from major fouling over the same period.

Cavitation inception itself is a complex phenomenon which is far from being completely understood at present. The mechanisms underlying this phenomenon are thought to be threefold: water quality (mainly nuclei content and its statistics); the growth of the boundary layer over the blade sections; and type of cavitation to be developed. Amongst them, it is most likely that the growth of the boundary layer will be most affected by the presence of coating while the type of cavitation may also be affected. In the case of a “surface” cavitation, as oppose to a “vortex” type, inception occurs in the region of the boundary layer transition. In this respect, propeller blade roughness stimulates the transition of the boundary layer from laminar to turbulent flow and hence causes cavitation inception. The Foul Release coatings are

expected to delay transition from the laminar to the turbulent flow and hence the associated delay in cavitation inception will also be expected. However, this effect may not be so important for full-scale propellers which operate in fully turbulent regime. Even if it is limited to the leading edge regions, this delay can be important for special propellers designed to avoid cavitation. In addition, from a cavitation point of view, blade roughness and fouling may create bubble residence locations and hence to reduce the cavitation strength of the water.

As far as the propeller noise is concerned, the broad-band noise is mostly affected by the level of turbulence in the incident flow and its interaction with the wall boundary layer which will be affected by the coating. One of the important mechanisms contributing to the broad-band noise is the trailing edge noise which is perhaps the least well understood mechanism of noise generation. The role of the turbulence in the boundary layer is a crucial parameter, which will be affected by the presence of the coating; this noise component would suffer from the effects of possible fouling with an uncoated propeller. In addition, the collapse of cavitation bubbles creates shock wave and hence cavitation noise. The presence of the visco-elastic foul release coating during the collapse may act as a damper absorbing the energy of cavitating noise, hence reducing noise level. This should be investigated experimentally to measure noise characteristics of a propeller both with and without the coating.

Within the above context an ongoing research programme has been established by the School of Marine Science & Technology of Newcastle University together with the International Paint Ltd, into the effect of coatings on the hydrodynamic performances of marine propellers. The experimental study presented in this paper is part of this ongoing research and investigates the effects of foul release coatings on the efficiency, cavitation and noise characteristics of a typical commercial vessel propeller. The paper presents the details of recent cavitation tunnel tests including the descriptions of the testing facility, model propeller and measurements of the open water performance, cavitation and noise as well as the analysis and discussion of the results obtained from these measurements.

2 EXPERIMENTAL SET-UP AND TEST CONDITIONS

The experiments were carried out in five groups at the Emerson Cavitation Tunnel (ECT), which has a large rectangular test section with a cross-section of 1.22 m x 0.81 m (BxH). Atlar (2000) gives a complete description of the facility.

The first group of experiments was the simulation of a target axial wake flow, which was selected to be suitable for the tanker propeller. The second group of tests involved the open water tests with the model propeller to investigate the effect of coating on the propeller performance in uniform flow. The third group comprised the cavitation inception measurements with the model

propeller in uniform and non-uniform flow conditions whilst the fourth group was the noise measurements with the model propeller in uniform and non-uniform flow conditions. The fifth and last group involved the surface characterisation measurements of the propeller blades with and without coating.

Table 1 A summary of test conditions

Test Group	Propeller Surface condition	Test Name	Flow Condition
1	-	Wake survey behind a wake screen	-
2	Uncoated	Open water tests	Uniform
	Coated	Open water tests	Uniform
3	Uncoated	Cavitation inception tests and observations	Uniform & Non-uniform
	Coated	Cavitation inception tests and observations	Uniform & Non-uniform
4	Uncoated	Noise measurements	Uniform & Non-uniform
	Coated	Noise measurements	Uniform & Non-uniform
5	Uncoated & Coated	Surface characterisation measurements	-

The simulation of the wake flow in the axial direction was carried out using different size of meshes attached to a wake frame; the wake velocities were measured using a pitot static tube comb and “Scanivalve” assembly. By following the standard procedure adopted in the ECT, a 0.5 m x 0.5 m wake frame to carry varying size of wire meshes was placed upstream of the propeller at a distance of approximately twice the model propeller diameter (~0.6 m). The pitot tube comb carrying five 2-holed tubes was mounted on the shaft of Kempf & Remmers H33 dynamometer downstream of the frame. The tunnel water velocity, V , was kept constant at 3 m/s and the velocity measurements were taken at the fractional radii of the propeller.

Open water tests were carried out according to the International Towing Tank Conference (ITTC) procedure for Open water tests (ITTC, 2005), using a Kempf & Remmers H33 dynamometer to measure torque and thrust values of the propeller. The tests were performed to cover the entire advance coefficient range (J), under the atmospheric condition and the tunnel water speed was kept at 3 m/s. By adjusting the rotational speed of the propeller (n), the advance coefficients were obtained. In order to obtain accurate results of the open water tests, the tests were repeated 10 times for each case. The thrust and torque values were, then, averaged.

Cavitation inception measurements were taken using a FlashCam Black & White CCD video camera with a fast electronic shutter, as well as by eye. The procedure for the inception measurements was performed such that the tunnel flow velocity was kept constant at 3 m/s. The tunnel static pressure was set to a constant value and the rotational speed of the propeller was initially increased until a visual appearance of tip vortex cavitation starting at the tip of the propeller, as an unattached nature. This was recorded as the inception of cavitation. The rotational

speed was, then, increased up to tip vortex cavitation developed on the blades and decreased until the tip vortex cavitation was disappearing at the tip of the propeller. This was accepted as the desinence cavitation. In addition to the above forms of the cavitation, one more stage of the cavitation development on the blades was observed and the associated inception points were recorded. This phase was the tip vortex cavitation “fully attached to all blades”.

Cavitation observations were taken using the same video camera for the fully loaded and ballast conditions at the advance coefficients given in Table 2.

Table 2 Full-scale data for fully loaded and ballast conditions

	Fully Loaded Condition	Ballast Condition
Cavitation number, σ	0.520	0.334
Propeller immersion, H (m)	10	4.66
Propeller speed (RPM)	100	104
Design J_A	0.48	0.486
J range tested	0.75, 0.70, 0.65, 0.60, 0.55, 0.50, 0.45, 0.40	

Noise measurements were carried out for fully loaded and ballast conditions in uniform and non-uniform flows, given in Table 2. The measurements were recorded using a Bruel and Kjaer type 8103 miniature hydrophone mounted in a water filled, thick walled, steel cylinder placed on a 30mm thick plexiglass window above the propeller at a vertical distance of 0.405m from the shaft centreline of the dynamometer. The signals from the hydrophone were collected by further Bruel and Kjaer equipment, in this case a PC based ‘Pulse’ digital acquisition and analysis system up to a frequency of 25 kHz. During the cavitation and noise measurements the dissolved gas content of the water was measured about 22%.

Surface characterisation measurements were performed using both a stylus and optical based measurement systems to compare roughness and texture characteristics of both uncoated and coated surfaces and also to cross check the results from both instruments. The stylus instrument was Surtronic 3⁺, which was only used for the uncoated blade surfaces. This was due to the fact that the sharp stylus would damage rather delicate foul release surface. It was, therefore, decided to use a laboratory based UBM optical measurement system which is a non-contact laser based instrument and suitable for foul release surfaces. However, as the model propeller blades have almost no flat surface this became a problem for the UBM device. In order to overcome this replicas of both sides of the uncoated blade surfaces were created, using a silicon rubber mixture which had a 4% silicon hardener (tetraethylsilicate). The silicon replica of the surface was removed carefully from the surface, representing the negative image of the real surface. To obtain the real surface, a casting resin was prepared and poured onto a flat plate with a thickness. The silicon negative image was, then, laid onto the resin and left there until completely dried. The silicon part was removed. The real

replica of the uncoated propeller blade thus was obtained on the surface of casting resin. These replicas were used on the UBM to measure surface characteristics of the uncoated blades to be able to compare with the results from the Surtronic 3⁺ device. For the coated surfaces, a sample of the first coating layer was applied onto a flat plate, then, the remaining two layers were applied onto the first layer and the second layer, respectively. At each stage surface measurements were taken using the UBM device.

2.1 Model Propeller

The propeller used for the tests was a model of the coated propeller from an existing 100,000 DWT tanker. The vessel has been actively monitored to investigate the performance of its coated propeller. The details of the basis vessel and its propeller are given in Table 3. The propeller was representative of typical modern merchant propellers and hence can be considered as the most likely representative for coating applications at full-scale. The model propeller was made from aluminium alloy with built-in blades. Figures 1 and 2 show the model without and with coating applied on the blades, respectively.

Table 3 Main particulars of the basis vessel and propeller

Propeller		Vessel	
Diameter, D	6.85 m	Ship type	Medium sized tanker
Pitch Ratio, P/D	0.699	Deadweight	96920 tonnes
Expanded Blade Area Ratio, A_E/A_0	0.524	Length Overall, L_{OA}	243.28 m
Number of Blades, Z	4	Max Draught, T	13.62 m
Design Advance Coefficient, J_A	0.48	Speed	14.86 knots
Direction of rotation	Right handed	Power (installed)	9893 kW
Scale ratio, λ	19.57	Built	1992



Figure 1 Model propeller with uncoated blades



(a)

(b)

Figure 2 Model propeller with coated blades: (a) thicker coating; (b) thinner coating

2.1.1 Paint Application to Propeller Blades at Model Scale

A standard paint application procedure to marine propeller blades has 4 layer coatings: 2 epoxy base coats, a silicon polymer top coat and a tie coat between these two in order to facilitate a good bonding between the epoxy and the silicone top. The whole system dries to a film thickness of about 350 μm . Unfortunately this four layer system resulted in rather thick paint around the trailing and leading edges of the blades as well as increased blade thickness. Initial tests conducted with this coating system displayed extremely low efficiency values, higher noise levels (high pitch singing) and unrealistic cavitation patterns compared to those obtained with the uncoated blades. In order to remedy this situation, it was decided to apply a 3 layer-coating system consisting of an epoxy base coat, a tie coat and a silicon polymer top coat, which dries to the thickness of about 250 μm on the propeller surfaces. This was the best practical application that was achieved within the limitations of our capability. Although further investigations would be required, it is strongly recommended that paint application to propeller blades at model scale should be the 3 layer-coating system and applied carefully in a laboratory condition.

3 PRESENTATIONS AND DISCUSSIONS OF TESTS RESULTS

3.1 Wake Simulation Tests

Simulated axial wake contour plot is shown in Figure 3 where 0° corresponds to the Top Dead Centre (TDC) of the propeller plane whilst 180° to the Bottom Dead Centre (BDC). In overall the calculated difference in the values of mean wake flow velocity ratio (1-w) for the target and achieved wake flow was 5.56% over the propeller disk. Nominal mean wake fraction (w) was obtained as 0.27 and this value was accepted as appropriate for this vessel.

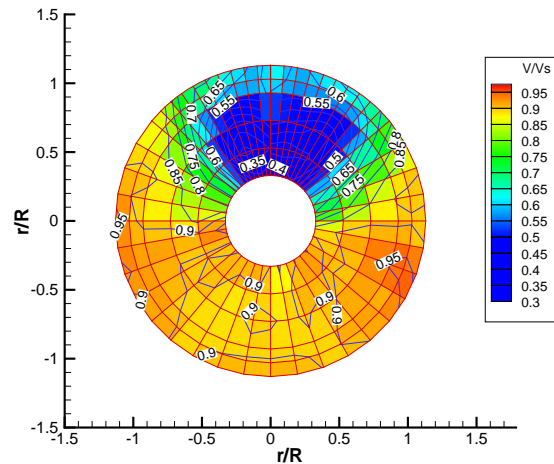


Figure 3 Simulated axial wake contour

3.2 Open Water Tests

Open water test results are shown in Figure 4 to compare the performance of the propeller with the uncoated and coated blades. In this figure propeller advance coefficient, J , thrust coefficient, K_T , torque coefficient, K_Q , and open water efficiency, η_0 are defined as

$$J = \frac{V}{nD}, K_T = \frac{T}{\rho n^2 D^4}, K_Q = \frac{Q}{\rho n^2 D^5}, \quad (1)$$

$$\eta_0 = \frac{J}{2\pi} \frac{K_T}{K_Q}$$

where V is the water velocity (m/s), n is the rotational speed of the propeller (rps), T is thrust (N), ρ is the density of water (kg/m^3) and Q is the torque (Nm).

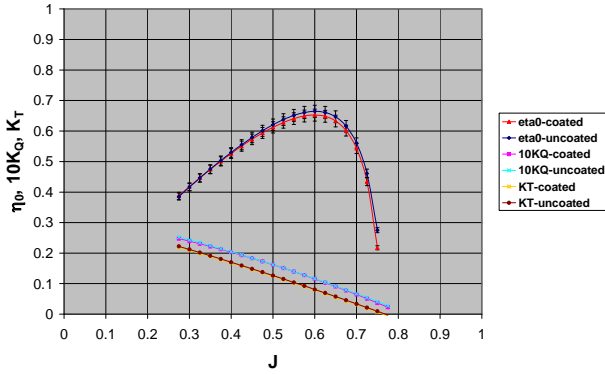


Figure 4 Comparison of open water test results for coated and uncoated cases

Thrust coefficients of the uncoated blades were slightly higher than to the coated case by an average of 1.9%. This was also valid for the torque coefficient values, hence the coated blades showed an average reduction of 0.9% when compared to those of the uncoated blades. Then, the average difference in the efficiency values was about 1%. In overall the differences obtained in the tests were within the uncertainty level of the open water tests, which was 3%. Mutton et al. (2005) also obtained similar results, using the same model propeller with the 3 layer coating system applied. Based on the present measurements and previous test results one can safely conclude that coating does not significantly effect thrust and torque characteristics of model propeller.

3.3 Cavitation Inception Tests and Observations

Table 4 shows cavitation inception tests results with uncoated and coated blades in both uniform and non-uniform flow cases. In this table, the inception number, σ_i is defined according to the mean cavitation number based on resultant or relative velocity, V_R , as

$$\sigma_i = \frac{P_{st} - P_v}{\frac{1}{2} \rho V_R^2} \quad (2)$$

where P_{st} is the static pressure at a reference point (0.7R) on the propeller blade (N/m^2) and P_v is the vapour pressure of water (N/m^2), $V_R = \sqrt{V^2 + (0.7\pi mD)^2}$.

Cavitation developments on different blade surfaces in uniform and non-uniform flow cases at varying advance coefficients for fully loaded and ballast conditions are given in Figures 5 and 6, respectively.

Table 4 Cavitation inception test results with uncoated and coated blades in uniform and non-uniform flow cases.

Cavitation Type	Uniform		Non-Uniform	
	Uncoated	Coated	Uncoated	Coated
Unattached tip vortex cavitation-inception	0.685	0.679	0.982	0.984
Unattached tip vortex cavitation-desinence	0.683	0.677	0.980	0.983
Attached to all blades	0.606	0.611	0.701	0.695

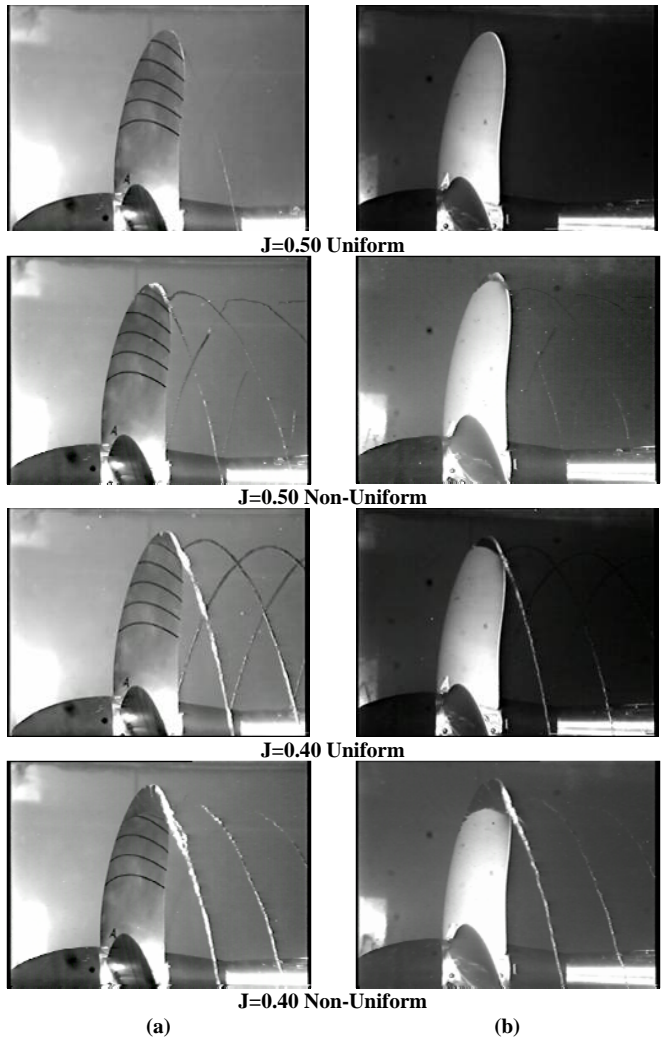


Figure 5 Cavitation developed in uniform and non-uniform flow conditions at varying advance coefficients for fully loaded condition: (a) uncoated; (b) coated.

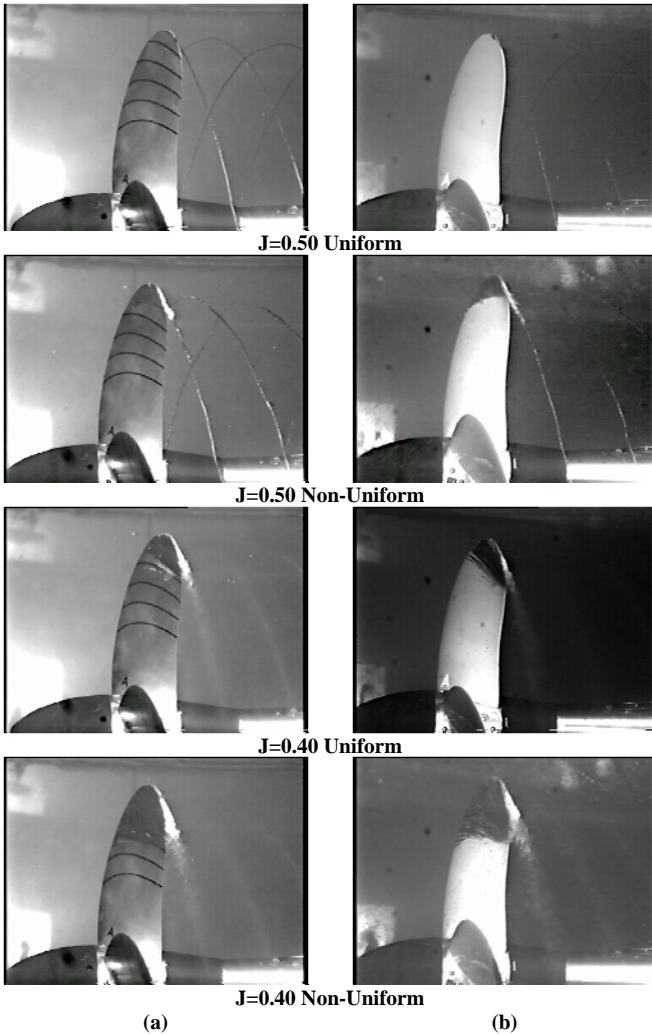


Figure 6 Cavitation developed in uniform and non-uniform flow conditions at varying advance coefficients for ballast loading condition: (a) uncoated; (b) coated.

For the inception and desinence of cavitation, an average difference between the results of the uncoated and coated blades was less than 1% in both uniform and non-uniform flows, as shown in Table 4. Although the cavitation results of the thicker coating case are not presented in this paper, this case displayed earlier inception values than other cases due to the increased blade thickness, particularly around the leading edge where the tip vortex cavitation usually occurs and the leading edge shape is sensitive to the inception. This applies to both uniform and non-uniform flow conditions. Therefore the coating of a propeller blade did not change the cavitation inception characteristics of the propeller when applied correctly.

As mentioned in Section 1, propeller blade roughness plays an important role for early cavitation inception by stimulating the transition of the boundary layer from laminar to turbulent. In this respect, the foul release coatings are expected to delay cavitation inception due to better roughness surface texture characteristics than those of the uncoated full-scale propeller blades. However, it was shown that roughness and surface texture characteristics of both uncoated and coated blades were

almost similar (see Table 6), resulting in similar cavitation inception values in the model cavitation tests.

As far as the coating effect on the cavitation extent was concerned, all the blade surfaces did not cavitate from the highest advance coefficient, $J=0.75$ to $J=0.55$ for the fully loaded condition in uniform flow. As the propeller loading increased, hence lowering the advance coefficient, the uncoated blades displayed slightly more cavitation extent than those of the coated blades from tip vortex to sheet type, as shown in Figure 5. In non-uniform flow, similar to the uniform flow condition, the blades with varying surface conditions did not cavitate from $J=0.75$ to $J=0.60$. Slightly more cavitation developments were again observed on the uncoated blades than those of coated blade surfaces at reduced advance coefficients, as shown in Figure 5.

In the ballast loading condition similar cavitation behaviours were observed in both uniform and non-uniform flow cases that is shown in Figure 6.

3.4 Noise Measurements

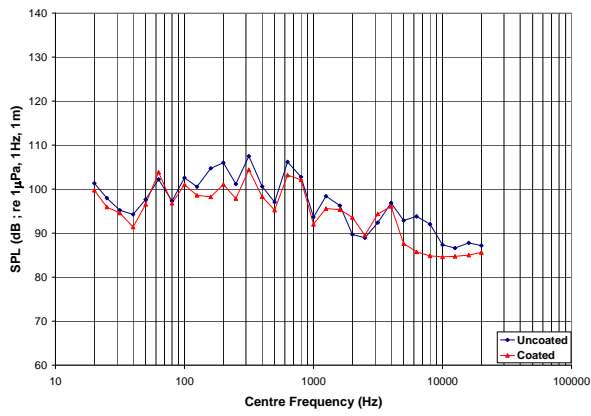
Although the noise measurements were taken in both uniform and non-uniform flow conditions, Figures 7 and 8 show the results for fully loaded and ballast conditions, respectively, for the uniform flow case only. A common practice in the analysis and presentation of the noise levels is to reduce the measured values of Sound Pressure Levels (SPL) in each 1/3 Octave band to an equivalent 1 Hz bandwidth by means of the correction formula recommended by ITTC (1978) as follows.

$$SPL_1 = SPL_m - 10 \log \Delta f \quad (3)$$

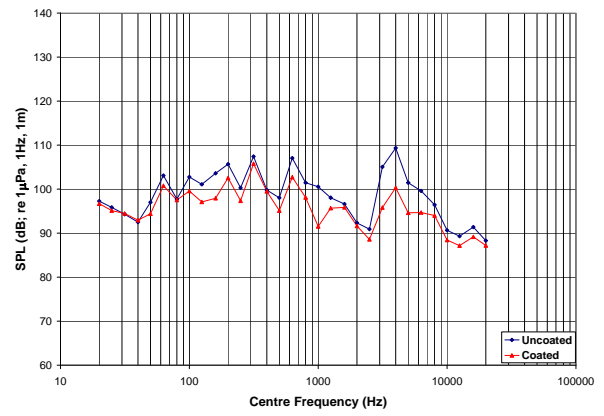
where SPL_1 is the reduced sound pressure level to 1 Hz bandwidth in dB; re 1 μ Pa, SPL_m is the measured sound pressure level at each centre frequency in dB; re 1 μ Pa and Δf is the bandwidth for each one-third octave band filter in Hz. The ITTC also required that the sound pressure levels be corrected to a standard measuring distance of 1 m using the following relationship.

$$SPL = SPL_1 + 20 \log(r) \quad (4)$$

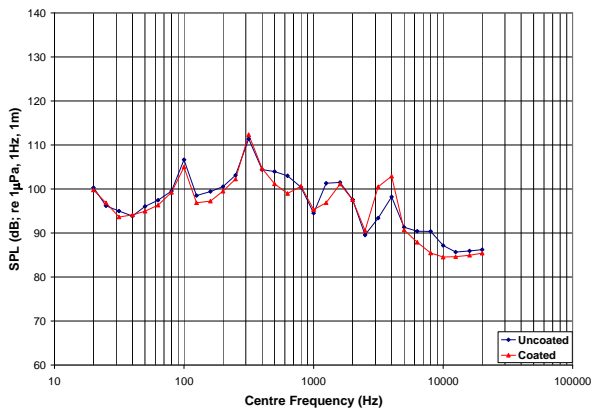
where SPL is the equivalent 1 Hz at 1 m distance sound pressure level (in dB; re 1 μ Pa) and r is the vertical reference distance for which the noise level was measured ($r=0.405$ m).



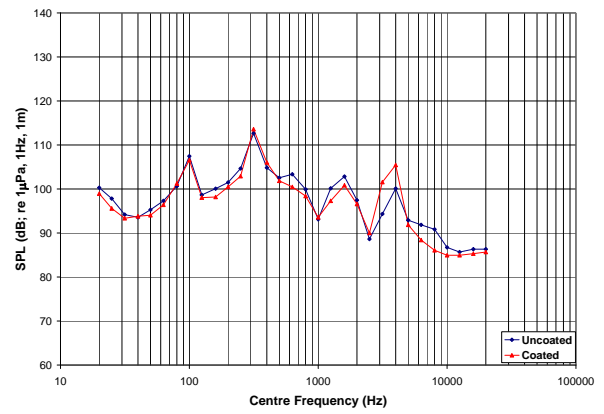
J=0.70



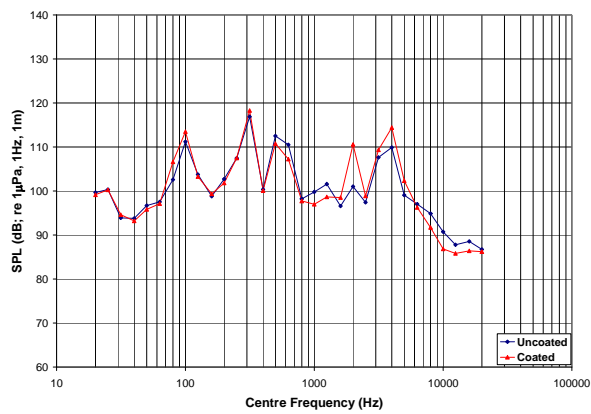
J=0.70



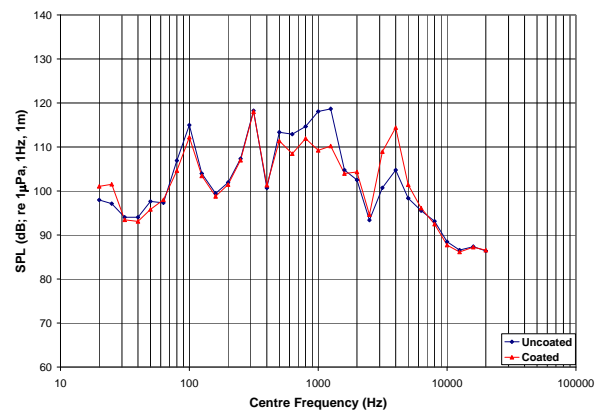
J=0.60



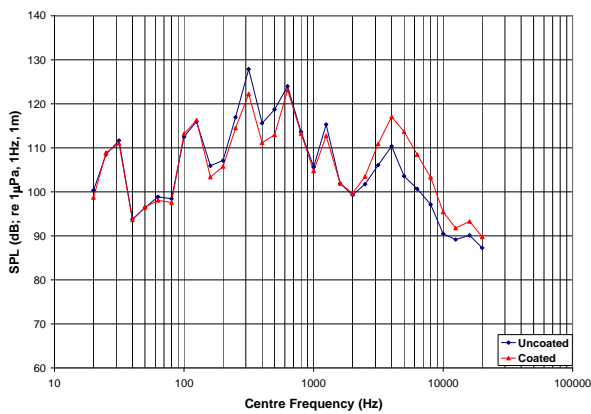
J=0.60



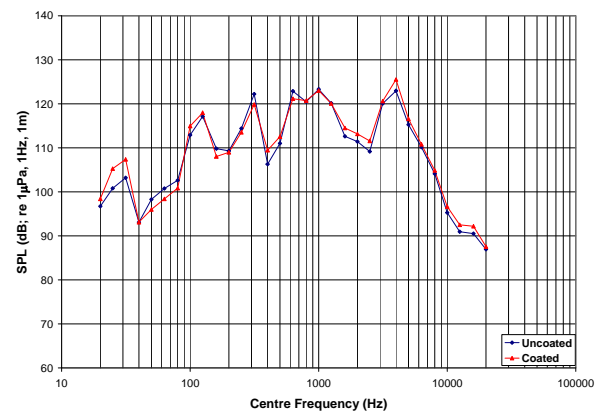
J=0.50



J=0.50



J=0.40



J=0.40

Figure 7 Effect of coating on noise levels of model propeller at varying advance coefficients in uniform flow for fully loaded condition.

Figure 8 Effect of coating on noise levels of model propeller at varying advance coefficients in uniform flow for ballast loading condition.

As far as the effect of coating on the noise levels was concerned, for fully loaded condition in uniform flow, the noise levels of coated blades were less than those of the uncoated blades at the advance coefficients of $J=0.75 \sim 0.60$. However at $J=0.50 \sim 0.40$ the coated blades displayed slightly higher noise levels in the high frequency region compared to the uncoated blade case (Figure 7). This confirmed the effect of developed cavitation on the noise levels. As the cavitation on the uncoated blades occurred earlier than the coated blades, hence developed more cavitation and entered stable state, this condition produced less noise level than the coated case. Therefore the cavitation development and its state played an important role in the noise levels. These trends were the same for the non-uniform flow case with different advance coefficients.

Similar trends were also observed for the ballast condition in both uniform and non-uniform flows. For the advance coefficients of $J=0.75 \sim 0.65$ in uniform flow, the uncoated blades again showed higher noise signals than the coated blades. As the propeller loading increased (from $J=0.55$ to 0.40) the coated blades showed slightly higher noise levels opposite to those at the high advance coefficient (Figure 8).

Therefore coating reduced the noise levels at the high advance coefficient, but increased the noise at the low advance coefficients for uniform and non-uniform flows.

3.4 Surface Characterisation

Tables 5 and 6 show the results of the surface characterisation using Surtronic3⁺ and UBM profilometer, devices, respectively.

Table 5 Roughness values of tanker model propeller with uncoated blades using Surtronic3⁺

Side	R _a (μm)	R _q (μm)	R _z (μm)	R _t (μm)	R _y (μm)	S _m (μm)
U-B	0.80	1.03	4.54	6.33	5.88	94.54
U-F	0.77	0.99	4.62	6.28	5.96	94.12
Mean	0.78	1.01	4.58	6.30	5.92	94.33

Table 6 Surface roughness characterisation measurements of different blade surfaces with UBM profilometer

Surface Cond.	R _a (μm)	R _q (μm)	R _z (μm)	R _t (μm)	R _{tm} (μm)	R _p (μm)	R _{pm} (μm)	F _D
U-B	1.56	2.1	41.52	48.23	24.4	35.77	16.5	2.42
U-F	1.9	2.9	65.6	117.9	33	72.7	19.9	2.46
U-M	1.73	2.5	53.56	83.07	28.7	54.24	18.2	2.44
C-C1	3.41	4.35	46.82	53.89	34.21	33.81	20.08	2.62
C-TC	2.6	3.3	96.9	125.1	39.9	1.15	32.5	2.11
C-Top C	4.14	5.18	62.73	76.54	40.13	57.2	28.71	2.26

In Tables 5 and 6, U-B denotes back side and U-F denotes face side of the propeller with the uncoated blades. R_a is the centre-line average roughness height, R_q is the Root Mean Square (RMS) roughness height, R_z is the vertical separation of the average of the 5 highest peaks and the average of the 5 lowest valleys, R_t is the highest peak to

lowest valley height, R_y is the largest peak to valley height within cut off length and S_m is the mean space between profile peaks at the mean line measured. In Table 6, U-M denotes the mean values of the back and face side, C-C1 denotes coated with epoxy base coat, C-TC denotes coated with tie coat and C-TopC denotes coated with top coat. R_p is the largest peak height, R_{pm} is the average of the peak heights and F_D is the fractal dimension.

As it can be seen in the above tables, the comparison of the measured roughness amplitude characteristics of the uncoated blades from the two different devices, which use different techniques, display significantly different results questioning the basis of such comparison. Although the use of stylus based Surtronic device is more direct way of measuring the blade surface characteristics its sharp stylus was problematic to measure the coated surfaces in model scale. Therefore, although it was an indirect way, the measurements of the uncoated and coated blade surface characteristics using the optical UBM device was the only available option for comparison given in Table 6. The comparison of the roughness amplitude values indicates that whilst the coating increased the roughness amplitudes across the table, it reduced the single texture amplitude, which is the fractal dimension value (F_D). This trend is expected since the application of the coating would increase the roughness amplitudes compared those of the uncoated blades with rather fine finish despite the smoothing effect of the coating. At the same time, inherent with the foul release coatings, the surface texture will become more "open" as reflected on the reduced F_D value. However, it should be born in mind that, although the roughness amplitudes of uncoated blades in model scale are expected to be smaller than those of coated blades, this may not be the case for uncoated blade surfaces with rougher finish in the full-scale as reported by Mutton et al (2005).

4 CONCLUSIONS

An experimental study was carried out to investigate the effect(s) of foul release coating on the performance, cavitation and noise characteristics of a tanker model propeller. Some conclusions drawn from the study are as follows:

- Owing to the practical limitation of this study the coating thickness applied to the model propeller was almost similar to the coating thickness at full-scale. This would require further investigation on scaled coating thickness and an appropriate scaling law.
- During the paint application at model scale particular care had to be taken to avoid paint sagging at the blade edges which could result in unrealistic cavitation pattern and singing. When applied correctly, propeller performance was maintained, indicating that coating may not cause any performance reduction.
- The coating of the blades did not change the cavitation inception characteristics of the model propeller. As the propeller loading increased, the uncoated blades displayed slightly more cavitation extent than those of the coated blades from tip vortex to sheet type for both loading conditions. Therefore

the coating slightly reduced the cavitation development on the blades.

- Whilst the coating of the blades reduced the noise levels in non-cavitating condition, it slightly increased in the developed cavitation condition. This finding applied to all loading conditions in uniform and non-uniform flows.
- Propeller blade roughness stimulates the transition of the boundary layer from laminar to turbulent flow and hence causes early cavitation inception. The foul release coatings are expected to mimic similar behaviour and hence possible delay in cavitation inception.
- In order to quantify the effect of foul release coating thoroughly at model scale one should simulate varying surface roughness parameters corresponding to full-scale propeller surface conditions in operation since the uncoated model propeller surfaces have very smooth characteristics, which make the comparison difficult with the performance of the coated blades.

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