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An Experimental Investigation into PressurePores™ Technology to Mitigate Propeller Cavitation and Underwater Radiated Noise

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Abstract: This paper presents a practical retrofitting technology, which is called "PressurePores™" technology, to reduce the cavitation induced noise from a marine propeller, and the results of an experimental investigation to show the merits of this technology for a more silent propeller. Strategically introduced PressurePores™ to the propeller blades, that may be producing limited thrust for the operating vessel due to the presence of cavitation, can reduce the overall cavitation volume, which would consequently result in a reduction of the radiated noise levels, while retaining the propeller's efficiency as much as possible.

To demonstrate this technology, in addition to the comprehensive CFD investigations, some cavitation tunnel tests and towing tank tests were conducted with the model propeller of a research catamaran for three different blade configurations. The first group of tests were conducted with the original propeller without any pore on its blades. The second group tests incorporated the PressurePores™ technology on the blades, while the third group was conducted with a reduced number of PressurePores™ on the blades. An overall finding from these tests indicated that a significant reduction in cavitation noise could be achieved (up to 17 dB) at design speed with a favourable PressurePores™ arrangement. Such reduction could be particularly effective in the frequency regions that are utmost important for marine mammals while this sub-cavitating propeller was losing only 2% of its efficiency. The extrapolation of the model scale noise measurements for the original propeller and its counterparts propeller blades with the PressurePores™ demonstrated that such an easy retrofit solution could significantly help the vessels to achieve, e.g. the industry-recognised DNV Silent notation, Environmental Transit noise levels.

Keywords: Pressure Relief Holes; PressurePores™; Cavitation Noise Mitigation; Experimental Hydrodynamics;

1 INTRODUCTION

The technological developments of the last half-century have revolutionised the world that we live in at the moment. One of the main driving factors for such swift advancement is the globalisation of the world. Commercial shipping has made globalisation possible by providing the most efficient means of transportation. With the ever-increasing world population and the fundamentals of economies of scale, the volume of commercial shipping has experienced an increasing trend over the last five decades. Unfortunately, this has also resulted in the elevation of emissions produced by the maritime industry IMO, (2013).

One of the most adverse by-products of the commercial shipping has been underwater radiated noise (URN) emission Ross, (1976). The extraordinary expansion of the world fleet has resulted in increased levels of the ambient noise in the world's seas, especially in the low-frequency domain Frisk, (2012). Unfortunately, this domain is also utilised by marine mammals for various fundamental living activities. Thus, exposing them to such an abrupt change in ambient noise levels may disorient them or disrupt their communication signals, leading to behavioural changes of these mammals or local extinction Richardson et al., (2013), White & Pace, (2010).

Within the framework described above, the recently conducted PressurePores™ Technology (Patent Application Number PCT/GB2016/051129) project aimed to explore the merits of implementing pressure relieving holes on marine propellers to mitigate the cavitation induced noise for a more silent propeller. This paper is associated with the presentation of the results from the experimental investigation of this project.

In order to achieve the aim of the project, first, a literature review was conducted in the related field. This revealed that in the late 90s, Sharma et al. from the Indian Institute

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of Technology in Bombay conducted research involving cavitation noise on marine propellers Sharma et al., (1990). In that study, Sharma et al. tried to delay the onset of the tip vortex cavitation and to reduce the produced noise without influencing the propeller performance adversely. Based on this rationale, Sharma at al. modified propellers by drilling 300 holes of 0.3mm diameter in each blade. These holes were drilled at the tip and the leading edge areas of the blades. Sharma et al. tests indicated that the dominant cavitation type at inception was the tip vortex cavitation under any testing conditions. The modifications did not demonstrate any measurable influence on the performance characteristics of any of the propellers tested. But, as it was expected, it had a great influence on the Tip Vortex Cavitation (TVC).

Regarding the acoustic benefit, there was a great improvement by the complete attenuation of the low-frequency spectral peaks, e.g. as shown in **Figure 1**. The tests with the original (unmodified) propellers showed a consistent rise of spectrum levels throughout the frequency range as the advance coefficients were reduced, but this was not the case for the modified propellers. The advance coefficients had a weak effect on the noise levels. This was attributed to the consequences of the modification where the tips were unloaded, and the suction peak in the leading edge was reduced while the TVC strength was reduced due to the increase in the angle of incidence.

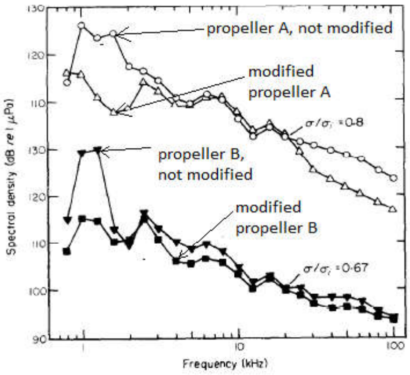

Figure 14 Influence of blade modification on cavitation noise for J=0.38. Sharma et al., (1990).

Figure 1 presents a comparison of the noise characteristics for the original and the modified propellers A and B at the advance coefficient of J=0.38. In such a low J value, the improvement was more significant. Particularly for low frequencies, between 1 and 2 kHz, a reduction of about 15 dB was observed in the noise levels of both propellers. In conclusion, "the modifications carried out had no measurable influence on the performance characteristics of the basic propellers". However, they achieved a delay in the onset of the cavitation and significant noise reductions. One interesting point to note in Sharma et al. 's work was that they tested all propellers in uniform flow conditions. This inherently disregards the presence of the ship hull in front of the propeller which is one of the most significant contributors to the cavitation and hence induced radiated noise.

To shed further light on this concept, and explore the effect of hull wake, an independent pilot experimental study was conducted in the Emerson Cavitation Tunnel of Newcastle University as part of an MSc study Xydis, (2015) by following Sharma et al., (1990). This pilot study was conducted using rather heuristic hole arrangements and limited test cases without any numerical optimization of these arrangements. While the study demonstrated some encouraging signs of the radiated noise reduction, the level of the reduction in cavitation extent to support this mitigation needed more sophisticated and detailed observations. Inspired from this MSc study, and based on the model propellers tested in the study, a comprehensive Computational Fluid Dynamics (CFD) based investigation was conducted by Aktas et al., (2018) to demonstrate the effectiveness of this mitigation method, which is later patented as the PressurePores^{TM} Technology by the sponsoring company. Based on the outcomes of this investigation, the best performing cases with the strategically selected PressurePores^{TM} were chosen to be tested at a towing tank for the efficiency measurements while at a cavitation tunnel for the cavitation and noise measurements to confirm the results of the CFD investigations. The results of the towing tank and Cavitation tunnel test have confirmed the findings of the high fidelity numerical simulation for the propeller efficiency and cavitation observations as well as confirming the significant reduction in the emitted cavitation noise levels (up to 17 dB). The reductions from the noise spectra are also found to be prominent in the frequency regions that can be important for some marine mammals while the propeller was loosing about 2% of its efficiency.

The detail of the experimental investigation summarized above is presented in this paper by the following layout; after this introductory section, Section 2 presents the description of the propeller model used as well as the experimental set-up and test conditions for the cavitation tunnel tests which were conducted in the University of Genova Cavitation Tunnel. Section 3 describes the details and results of the cavitation observations while Section 4 presents those of the radiated noise measurements. In Section 5 the details and results of the propeller performance tests, which were conducted in the CTO towing tank of Gdansk, and finally Section 6 presents the main conclusions obtained from the investigations.

2 PROPELLER MODEL, EXPERIMENTAL SET UP & TEST CONDITIONS

The experimental approach adopted in this study necessitated the use of several experimental artefacts. These included a propeller model that has two modified versions incorporating the PressurePores^{TM} technology, a cavitation tunnel and a towing tank described in the following. The adopted experimental test matrix is also provided.

2.1 Propeller Model

The propeller model used for both tests represented the port side propeller of the Newcastle University's research catamaran, *The Princess Royal* with a scale ratio of *3.409*, giving a *220mm* model propeller diameter. The reason was selecting this propeller as the test case two folds: firstly this vessel has become almost benchmark vessel worldwide for the URN and cavitation investigations; secondly, the Authors had extensive information and access to this vessel which can be used for validating the investigation in full-scale as part of the PressurePore™ technology project.

The propeller model was manufactured with high accuracy by considering the cavitation testing as shown by the deviation contour plot given in Figure 15. The principal dimensions of the full-scale propeller are given in Table 1.

Table 7 Propeller main characteristics and particulars

Full Scale Diameter [m]	0.75
Pitch Ratio at 0.7R	0.8475
Expanded Blade Area Ratio	1.057
Number of blades	5
Rake angle	0°
Skew angle	0°

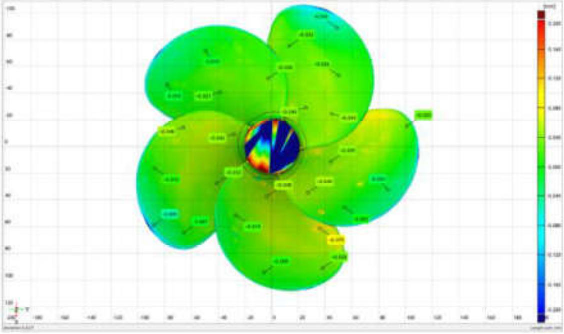

Figure 15 Manufacturing accuracy Image of the Princess Royal Propeller

The application of the PressurePore™ technology to this benchmark test propeller utilised the knowledge and experience gained through the CFD investigations conducted with this propeller as well as another test case propeller, which belonged to a 95000 tonnes merchant tanker, and tested in the Emerson Cavitation Tunnel by Xydis, (2015). In these investigations, the pore configurations applied were simulated initially by using the earlier version of the TVC model developed, and later by using the state of the art adaptive mesh refinement technique of Yilmaz et al., (2017). Based on these investigations, two sets of PressurePores™ configurations were selected to be tested at the CTO towing tank for accurate prediction of the propeller open water performance parameters and in the University of Genova cavitation tunnel for the cavitation observation and underwater noise measurements. The selected PressurePore™ configurations are shown in Figure 3 and 4, as applied on the model propeller, and represented by the following legend: "Modified Propeller" and "Modified Propeller-2", respectively. The diameter of the pores is 1mm, and 33 pores were used for the Modified propeller while 17 pores for the Modified-2 propeller model.

Figure 16 PressurePores™ as applied on The Princess Royal propeller for Modified Propeller

Figure 17 PressurePores™ as applied on the Princess Royal propeller for Modified Propeller-2

2.2 Experimental testing facilities

As stated earlier, two testing facilities were used for the experimental investigations. These were the medium-size cavitation Tunnel of the University of Genoa (UNIGE) and the large towing tank of the Centrum Techniki Okrętowej S.A. (CTO) Model Basin in Gdansk.

The cavitation tunnel of the University of Genova (UNIGE) is a Kempf & Remmers closed water circuit tunnel, schematically represented in Figure 4. The tunnel has a square testing section of 0.57m×0.57m, having a total testing section length of 2m. The nozzle contraction ratio is 4.6:1, allowing to achieve the maximum speed in the test section of 8.5 m/s. The tunnel is equipped with a Kempf &

Remmers H39 dynamometer, which measures the propeller thrust, the torque and the rate of revolution.

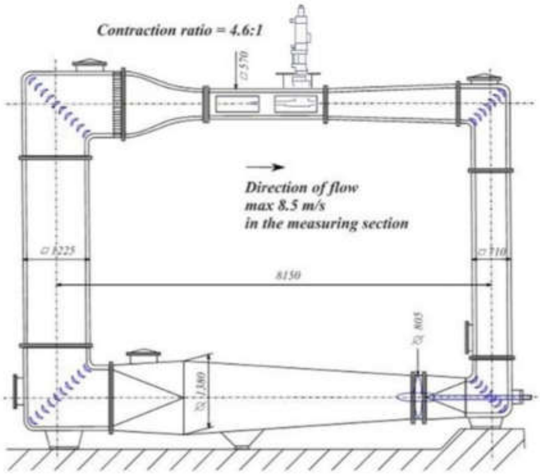

Figure 18 UNIGE cavitation tunnel

The CTO towing tank is approx. 270 m x 12 m x 6 m in length, breadth and depth respectively and is fitted out with a towing carriage of a maximum speed of 12 m/s. The performance of the propeller model before and after the application of the PressurePores™ technology was measured by using the standard open water dynamometer as shown in Figure 6.

Figure 19 Towing tank open water test set-up

2.3 Test set-up and test matrix

The test set-up used for the cavitation tunnel tests is shown in Figure 7. In order to simulate the tests in realistic operational conditions, the cavitation tunnel tests were carried out behind a simulated (nominal) wake field which was produced based on the wake survey conducted at the Ata Nutku Towing tank of Istanbul Technical University, Korkut & Takinaci, (2013). For this purpose, a wire mesh wake screen was built in the cavitation tunnel test section and resulting wake filed was verified by using a 2D Laser Doppler Velocimetry (LDV) device. The cavitation tunnel setup is schematically presented in Figure 20.

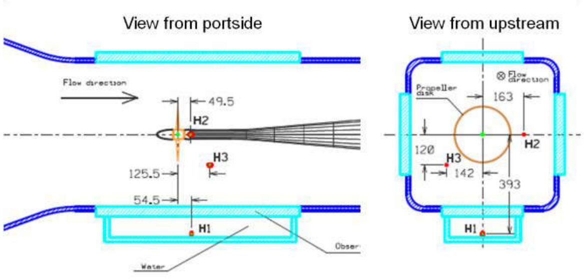

Figure 20 Cavitation tunnel setup, longitudinal view.

The comparative velocity distributions of the simulated wake in the UNIGE tunnel measured by the LDV, and that of the nominal wake measured in the ITU towing tank can be seen in Figure 8. As shown in the top section of Figure 8, a part of the wake data measured in the UNIGE tunnel is missing due to the limitation of the optical access for the LDV which was caused by the obstruction of the propeller shaft. The LDV measurements could be carried out by the probe that could approach to the measurement zone only from the starboard side of the test section.

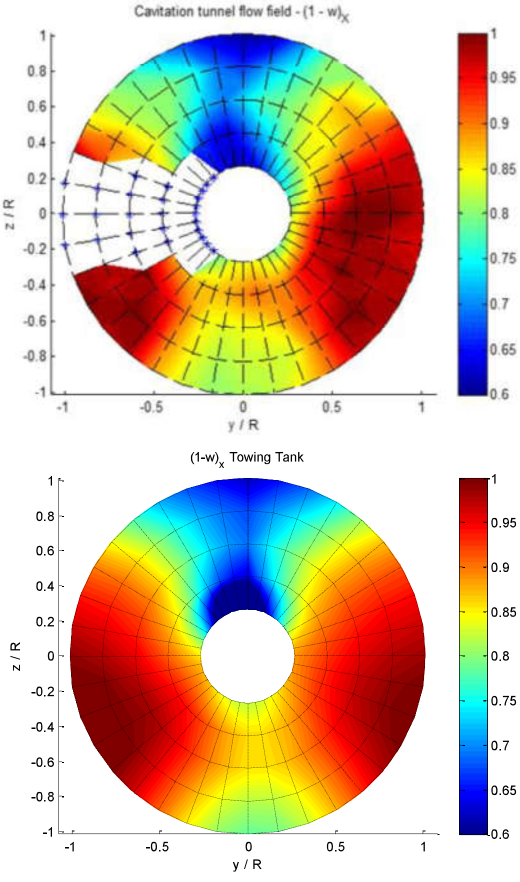

Figure 21 Nominal wake field: Simulated in cavitation tunnel (top); Measured at towing tank (bottom).

Based upon the typical in-service operational conditions of The Princess Royal, which correspond to 10.5kn and 15.1 kn vessel speeds, the cavitation tunnel test matrix is constructed as shown in Table 2.

Table 8 full-scale operational conditions during sea trials

Condition	Engine [RPM]	Shaft [rps]	STW (kn)	K_T	10KQ	σ_N (nD)
V1	1500	14.3	10.5	0.211	0.323	1.91
V2	2000	19.0	15.1	0.188	0.318	1.07

In Table 2 STW represents the vessel speed through the water. K_T and K_Q are the standard thrust and torque coefficient, respectively, while the cavitation number is defined based on the propeller shaft speed using Equation (1):

$$\sigma_n = \frac{P_a + \rho g h_s - P_v}{0.5\rho(nD)^2} \qquad (1)$$

where P_a is the atmospheric pressure, g is the gravitational acceleration, ρ is the density of water, h_s is the shaft immersion of the propeller, P_v is the vapour pressure, n is the propeller shaft speed in rps, and finally D is the diameter of the propeller.

Table 9 Non-dimensional performance and operational parameters for propellers

Performance Characteristics	**Symbol**	**Formula**
Thrust coefficient	K_T	$\frac{T}{\rho n^2 D^4}$
Torque coefficient	K_Q	$\frac{Q}{\rho n^2 D^5}$
Advance coefficient	J	$\frac{V_a}{nD}$
Efficiency	η_0	$\frac{J \times K_T}{2\pi \times K_Q}$

where T is the thrust, V_a is the advance velocity, Q is the torque and η_0 is the propeller efficiency.

The model scale test conditions were specified according to the thrust coefficient identity. As shown in Table 2, while Condition V2 corresponded to the actual service speed of the research vessel, Condition V1 corresponded at 10.5kn speed condition.

The cavitation tunnel tests were completed in three stages: the first stage involved the tests with the original propeller model with no pore (Intact propeller). The second stage, the propeller model with 33-1mm pores on each blade (Modified propeller); and the third and final stage, with 17-1mm pores on each blade (Modified-2) which was achieved by closing a half of the pores on the Modified propeller with an adhesive material and smoothening them with care.

During the tests, the water quality was assessed based on the dissolved oxygen content of the tunnel which was monitored by using the ABB dissolved oxygen sensor, model 8012/170, coupled with an ABB analyser model AX400.

3 CAVITATION OBSERVATIONS

In order to make qualitative comparisons between the cavitation experienced by the intact and modified propeller cases, cavitation observations were carried out. For this purpose, a mobile stroboscopic system was utilised to visualize and record the cavitation phenomenon on and off the propeller blades. The cavitation recordings were made with three Allied Vision Tech Marlin F145B2 Firewire Cameras, with a resolution of 1392 x 1040 pixels and a frame rate up to 10 fps.

Table 10 Cavitation observations for V1 and V2 for Intact and Modified propeller

Condition	**K_T**	**σ_N**	**Intact propeller observations**	**Modified propeller observations**	**Modified Propeller-2 observations**
V1	0.211	1.91	TVC everywhere, starting from blade L.E.; S.S. sheet cavitation at 0°, from 0.8R to the tip, for 15% of the chord at 0.8R, 100% at 0.97R; S.S. sheet cavitation at 180°, from 0.85R to the tip, for 10% of the chord at 0.85R.	Pores cavitation everywhere; TVC at 0° and 180°, only cloudy vortex at other positions; S.S. sheet cavitation at 0°-45° from 0.8R for 10%of the chord, merging with holes cavitation at outer radii; S.S. sheet cavitation at 180°, from 0.85R for 5% of the chord, merging with holes cavitation at outer radii.	Pores cavitation everywhere; TVC everywhere, at 90° and 270° the cavitating core is at inception; S.S. sheet cavitation at 0°, from 0.8R, for 15% of the chord, at 180°, from 0.85R for 10% of the chord.
V2	0.188	1.07	TVC everywhere, starting from blade L.E.; double vortex at 0°-60°; S.S. sheet cavitation at 0°, from 0.8R to the tip, for 50% of the chord at 0.8R, 100% at 0.85R; S.S. sheet	Pores cavitation everywhere; TVC everywhere, with double vortex at 0°-60°; S.S. sheet cavitation at 0°-45° from 0.8R for 30%of the chord, merging with holes	Pores cavitation everywhere; TVC everywhere, the cavitating core is now well developed but still presents unstable

			cavitation at 90° and 270°, from 0.9R for 10% of the chord; S.S. sheet cavitation at 180°, from 0.83R to the tip, for 50% of the chord at 0.83R, 100% of the chord at 0.92R	cavitation at outer radii; S.S. sheet cavitation at 180°, from 0.83R for 20% of the chord, merging with holes cavitation at outer radii.	behaviour; double vortex at 0°; S.S. sheet cavitation at 0° from 0.8R for 40% of the chord, at 180° from 0.8R for 30% of the chord.

Condition V1

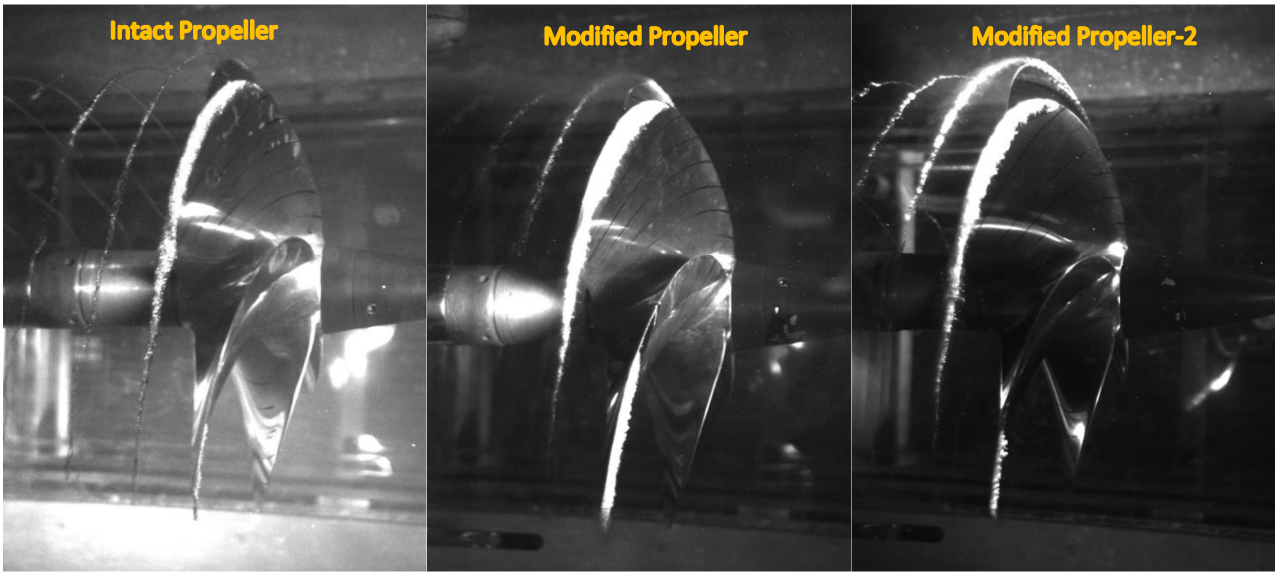

Figure 22 Intact vs Modified propeller and Modified Propeller-2, condition V1, viewed from starboard

Condition V2

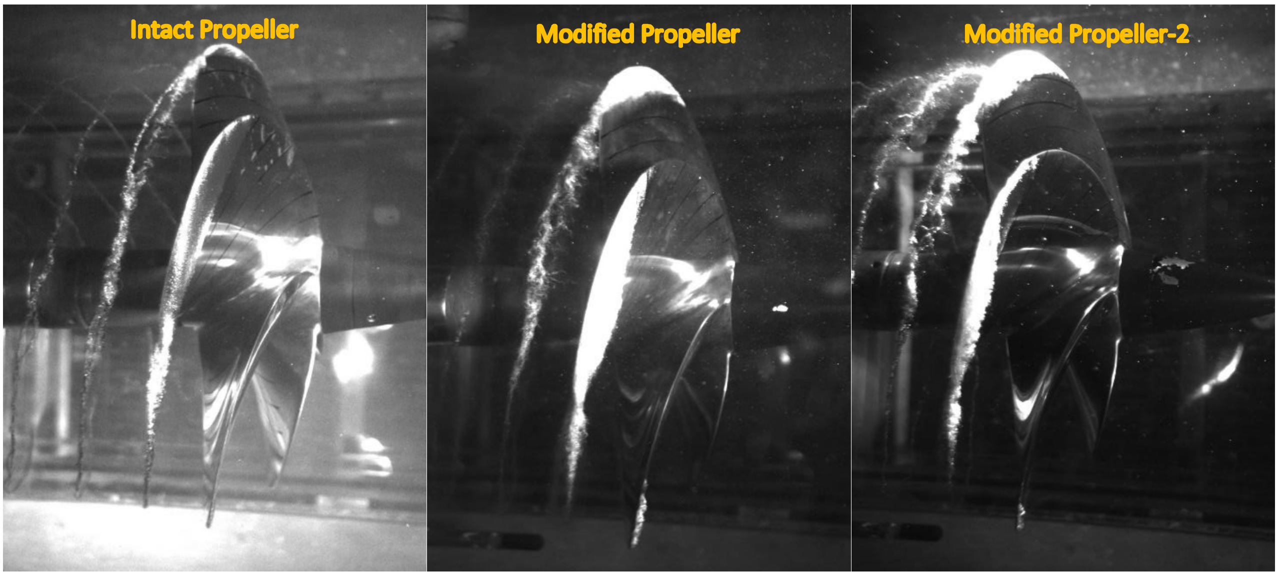

Figure 23 Intact vs Modified propeller and Modified Propeller-2, condition V2, viewed from starboard

4 RADIATED NOISE MEASUREMENTS

In this section the details of the test set-up for the noise measurements, the analyses and presentations of he these measurements and results are presented.

Figure 20 shows a scheme of the setup adopted during these tests including the positions of the three hydrophones utilized. In particular, two hydrophones were mounted on fins at the downstream of the propeller: one on the port side at the same vertical position with the propeller shaft (H2); the other (H3) on the starboard at a lower vertical position. The third hydrophone (H1) was mounted in an external plexiglass tank filled with water and mounted on the bottom window of the testing section. The measurements from H3 was used for the noise results presented throughout this manuscript.

Moreover, noise tests were also repeated at least three times. For the post-processing of the noise measured the ITTC, (2017) guidelines for the model scale noise measurements were followed.

The average Power Spectral Density, G(f) in Pa^2/Hz, was computed from each sound pressure signal p(t) using Welch's method of averaging modified spectrograms. The Sound Pressure Power Spectral Density Level Lp is then given by Equation (2):

$$L_p(f) = 10\log_{10}\left(\frac{G(f)}{p_{ref}^2}\right) \quad (\text{dB re } 1\ \mu\text{Pa}^2/\text{Hz}) \qquad (2)$$

where $p_{ref} = 1$ µPa.

The background noise was measured reproducing the same condition for corresponding test conditions regarding the shaft revolution, flow speed and vacuum by replacing the propeller with a dummy hub. Only one series of the background noise measurements were carried out since the tunnel operational conditions do not vary significantly passing from the intact to the modified propeller cases.

Comparing the total noise measured with the background noise, the net sound pressure levels of the propeller were analysed as follows:

1. Signal to noise ratio higher than 10 dB:
   No correction made
2. Signal to noise ratio higher than 3 dB but lower than 10dB:

$$\mathrm{L_{PN}} = 10\mathrm{Log}_{10}\left[10^{(\mathrm{L_{Ptot}}/10)} - 10^{(\mathrm{L_{Pbg}}/10)}\right] \qquad (3)$$

3. Signal to noise ratio lower than 3 dB:

Results disregarded (4)

Also, the net sound pressure levels may be scaled to a reference distance of 1-meter exploiting measured transfer functions, or simply according to Equation (5):

$$\mathrm{L_{PN@1m}} = \mathrm{L_{PN}} + 20\mathrm{Log}_{10}(\mathrm{r}) \qquad (5)$$

where r is the distance between propeller (acoustical centre) and sensor.

The latter formulation has been used in present work.

The acoustical centre of the propeller has been defined with respect to the centre of the propeller disk.

Based upon the above-described post-processing, Figure 11 to Figure 14 present the measured noise levels for the Intact propeller, Modified propeller and Modified Propeller-2 in the narrow and Third-octave band for condition V1 and V2. In both cases, significant reductions regarding the radiated noise levels can be observed over a frequency range from 200Hz to 1kHz. For the service speed condition V2, the reductions are consistent almost throughout the entire frequency range tested. For condition V1, the application of the PressurePores™ Technology observed to cause some elevation of the URN in the high-frequency region.

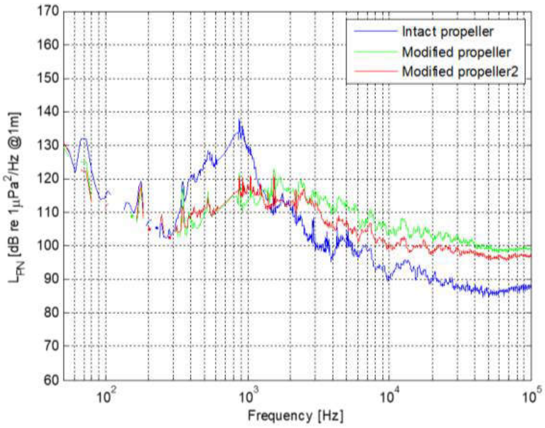

Figure 24 Comparison between Intact, Modified propeller and Modified Propeller-2 net noise levels at 1m (narrowband), condition V1, hydrophone H3

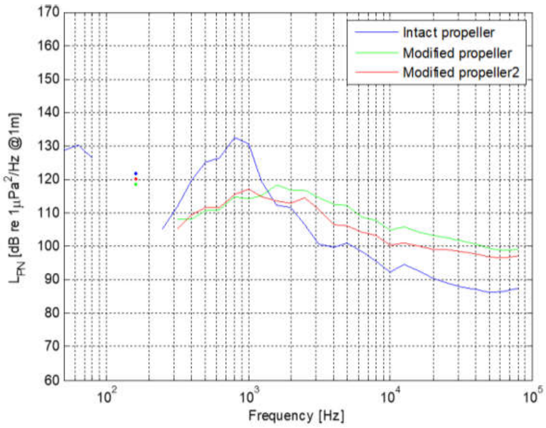

Figure 25 Comparison between Intact, Modified Propeller and Modified Propeller-2 net noise levels at 1m (one third octave band), condition V1, hydrophone H3

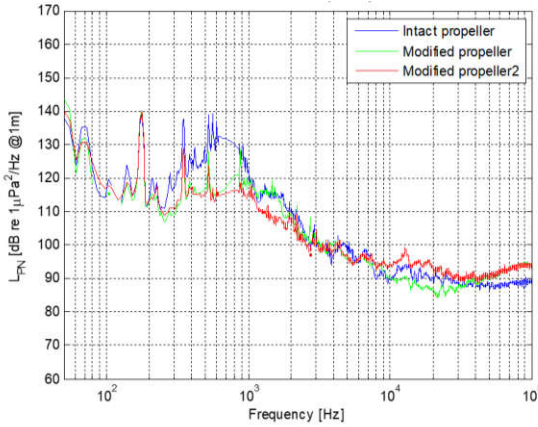

Figure 26 Comparison between Intact, Modified propeller and Modified Propeller-2 net noise levels at 1m (narrowband), condition V2, hydrophone H3

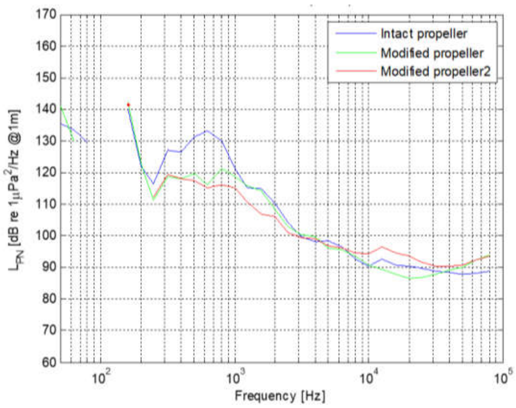

Figure 27 Comparison between Intact, Modified Propeller and Modified Propeller-2 net noise levels at 1m (one third octave band), condition V2, hydrophone H3

Figure 28 presents the net difference between the noise levels of the Intact propeller and both modified propellers for Condition V2 as measured by hydrophone H3 to demonstrate effectiveness of the PressurePore^{TM} technology.

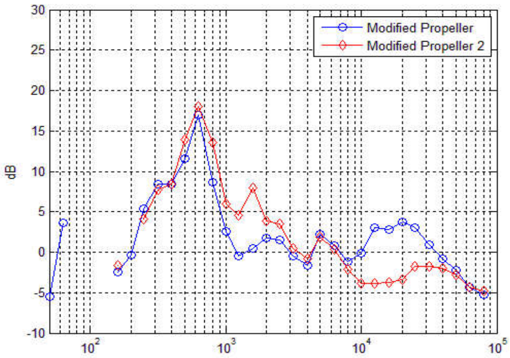

Figure 28 Noise reduction with application of pressure relief holes in Third Octave band for condition V2, measured at hydrophone H3

5 PROPELLER PERFORMANCE TESTS

This section presents the details and results of the propeller open water tests that were conducted at the CTO towing tank. The purpose of these tests was to determine performance characteristics of the propeller regarding thrust, torque and efficiency before and after the introduction of the PressurePores^{TM} technology.

During these tests, the rate of the propeller shaft revolutions was set over a range to assure the Reynolds Numbers above the critical threshold of 500,000. Also, to confirm the typical convergence of the measurements, for single advance ratio of J = 0.6, the tests were repeated for three additional values of the Reynolds number. The test data analysed for the thrust, torque and efficiency were presented by the 4th-degree polynomials for the three propeller test cases as shown in Figure 16.

The operating condition of the Princess Royal propeller are very close to Advance Coefficient J=0.5. As shown in Figure 4, the open water tests indicated that there is a 2% loss of thrust and 4% gain in torque which consequently results in a propeller efficiency loss of 5.7% for Modified Propeller compared to the intact propeller. For Modified Propeller-2 case, with a half of the pores applied in the Modified propeller test case, the loss in thrust was about 0.1% while there was a 2.2% gain in torque which resulted in the efficiency loss of 2.3%.

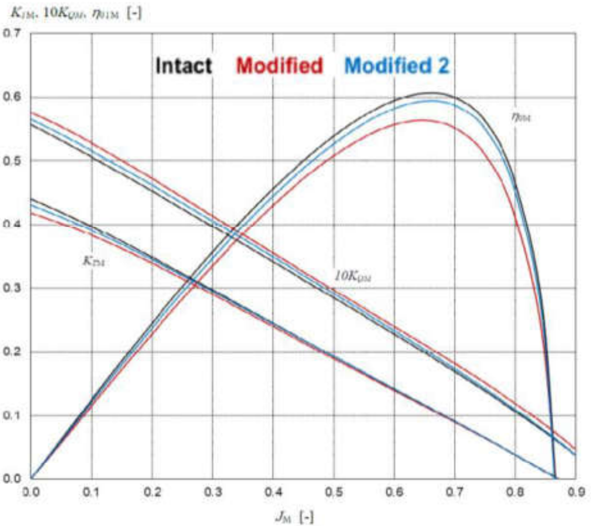

Figure 29 Open water characteristics of the PR propeller before and after the application of PressurePores^{TM} (Modified propeller and Modified Propeller-2)

6 CONCLUSIONS

PressurePores^{TM} Technology, which has been recent endorsed to reduce the cavitation induced noise of marine propeller, was validated by using model tests conducted in the University of Genova cavitation tunnel and CTO towing tank for the cavitation, noise and efficiency performances.

The test results conducted with the model propeller of a research vessel and for two different combinations of the PressurePores^{TM} technology indicated that significant reductions in the measured propeller noise levels can be achieved.

The comparative test results for the Modified Propeller test case indicated the noise reduction compared to the unmodified propeller can be as high as 17dB and particularly in the frequency region that are utmost important for some marine mammals. For the same configuration, the towing tank test data showed about a 2% loss in the propeller efficiency.

The test results for the Modified Propeller showed more superior underwater noise reduction in the high-frequency region but with a higher propeller efficiency loss, about 5.7%.

Acknowledegments
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