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An Experimental Study on the Effect of IS700 Coating on the Cavitation Inception and Development, and Noise Reduction of a Marine Propeller

Bagheri MR, Seif MS and Mehdigholi H*

Department of Mechanical Engineering, Sharif University of Technology, Center of Excellence In Hydrodynamics and Dynamics of Marine Vehicles, Iran

Abstract

In this paper, cavitation inception and development conditions are studied for five-blade propellers by experiments carried out in cavitation tunnel. Propeller noise is measured in different operating conditions for uncoated and coated propellers and also, the effects of silicone foul release (FR) coating, inter sleek 700 (IS700), are investigated on the cavitation delay and noise reduction of a marine propeller in cavitation tunnel. Finally, results are presented in low advance coefficients for cavitation inception and development, and noise reduction. These results can be applied as a reference for validating this propeller model in numerical simulations.

Keywords: FR coatings; Cavitation tunnel tests; Cavitation inception and development; Propeller noise

Abbreviations: FFT: Fast Fourier Transform; FR: Foul Release; IS900: Inter Sleek 900; IS700: Inter Sleek 700; SPL: Sound Pressure Level

Introduction

Paint coatings on ships and propulsion system have a wide range of functions such as corrosion resistance, ease of maintenance, delaying the cavitation phenomenon, propeller noise reduction and control, appearance, non-slip surfaces on decking as well as prevention of fouling on the hull by unwanted marine organisms [1]. Current technologies employ two basic strategies for non-biocidal coatings: antifouling (AF) and fouling release (FR) [2]. Reduction of fluid frictional drag and cavitation inception delay are both very important hydrodynamic problems in practical applications, and many studies on drag and cavitation reduction have been done over the years [3]. It is well known that the FR coating undergo drag reduction in the turbulent flow range. Recently it has been suggested that FR coating be applied to the frictional drag reduction and cavitation delay for ships and their propulsion system. A number of possible propeller coating types were introduced in order to use for different purposes. The several types were investigated by Coldron and Condé [4], Brasseur et al. [5], Li et al. [6], Winkel et al. [7], Somandepalli et al. [8], Elbing et al. [9], Demirel et al. [10] and Song et al. [11].

The FR coatings have many advantages including; less paint and less weight, long lasting, lower fuel consumption and less emission [12]. Some studies were performed on the effects of coatings on the drag, resistance, efficiency and cavitation of marine propellers. One of the most important specifications of silicone FR coatings is their effect to alter the turbulence characteristics of the flow near the wall. The silicone FR coatings were expected to delay such transition from the laminar to the turbulent flow and, therefore the occurred delay in cavitation inception will also be expected [13]. Intersleek 700 (IS700) and Intersleek 900 (IS 900) are two commercial coatings based on silicone FR coating. The IS700 is a hydrophobic silicone with a smooth and non-stick surface and the IS 900 is an amphiphilic coating from a blend of fluoropolymer and silicone with a smooth, slippery and glossy surface [14]. Detty et al. [15] concluded that the IS700 and IS 900 coatings, with nearly identical values of elastic modulus, surface energy, and roughness were the “best” and “worst” surfaces, respectively, for FR coating behavior. Also, Mieszkin [16], considered interactions between coatings and concluded that the IS700 has wettability properties better than IS 900 including; static, advancing and receding water contact angles.

Candries et al. [17] investigated the effects of FR coating on the drag and resistance characteristics. Cavitation is a major source of noise in the propellers and thus should be thoroughly investigated and decreased [18]. Atlar et al. explored that the effect of FR coatings on the propeller cavitation inception and development can be important as on its efficiency [19,20]. The effect of FR coating on the cavitation inception was first reported by Mutton et al. [21]. They concluded that the tip vortex was thicker in uncoated propeller while the extent of sheet cavitation was relatively large compared to the coated propeller. Korkut et al. [22], conducted further experimental investigations onto the effect of coatings on the cavitation inception and development using IS 900 coating. In another study by Atlar et al. the cavitation inception and extent characteristics of the model propeller were compared for uncoated, coated with IS900 and TNO-E008 cases [23]. The nature of the TNO-E008 coating and the application technology enabled to apply this coating at a desired thickness to achieve an average roughness which was 54% less than the roughness achieved with the IS 900. They concluded that the TNO-E008 coating gave a higher thrust value for the same rpm when compared to the IS 900 coating.

Much experimental research has been conducted to measure the propeller noise in the cavitation tunnel. Sharma et al. [24], measured the noise for some marine propellers in cavitation tunnel. Atlar et al. [25], carried out cavitation tunnel tests for propeller noise of an FRV. In a later study, Wang et al. [26], investigated cavitation and noise characteristics of ocean stream turbines. Emin et al. [27], did an experimental study into the effect of FR coating on the efficiency, noise and cavitation characteristics of a propeller. Park et al. [28], studied noise source localization in a cavitation tunnel. Bagheri et al. [29] predicted marine propeller noise under cavitating and non-cavitating conditions by experimental and numerical methods. In

***Corresponding author:** Mehdigholi H, Department of Mechanical Engineering, Sharif University of Technology, Center of Excellence In Hydrodynamics and Dynamics of Marine Vehicles, P.O. Box 16765-163, Iran, Tel: (+98) 2166005817; E-mail: mehdi@sharif.edu

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above-mentioned studies [24-29], propeller noise was just measured in cavitation tunnel. Cavitation decrease has many effects on reducing propeller noise. Similar to the lack of research on FR coating effects on cavitation delay, there are also few publications on the effect of FR coatings on propeller noise. Cavitation delaying to decrease propeller noise is an interesting and important research subject for marine propellers which should be considered thoroughly. Until now, the effects of IS 900 and TNO-E008 coating were investigated on cavitation delay and noise reduction of three and four blade propellers in [19-23].

In the present study, cavitation inception and development conditions are investigated for uncoated and coated cases for a five blade propeller by an experimental method in cavitation tunnel. Open water curves are presented and compared for the uncoated and coated propellers. Also, propeller noise is measured and compared in uncoated and coated propellers for different operating conditions. IS700 has been selected as recommended in references [14-16], therefore, the main innovation and motivation of this investigation is to consider of IS700 coating effects on the hydrodynamic, cavitation inception and development characteristics and noise reduction of a five blade propeller.

Experimental Set Up and Test Conditions

Open water tests are carried out according to the ITTC procedure using K23 cavitation tunnel. The K23 cavitation tunnel, located at the Center of Excellence in Hydrodynamics and Dynamics of Marine Vehicles (CEHDMV) in Sharif University of Technology is a recirculation tunnel with a rectangular measuring section, 2300 mm long, 650 mm wide and 350 mm deep. The cavitation tunnel test section and cavitation tunnel's specification can be seen in Figure 1 and Table 1 respectively.

The dissolved oxygen during the tests was about 65% to 80%. The common air content of the water in the tests performed by the research community is about 70% in accord with the Specialist Committee on Water Quality and Cavitation Express [30]. A Sony alpha SLT-α 33 video camera, with an appropriate electronic shutter, was used for video recording and image capturing of cavitation inception and development.

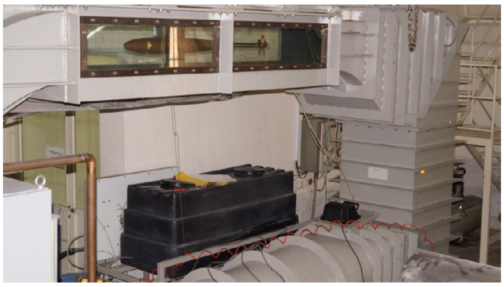

Figure 1: Test section K23 cavitation tunnel.

Cavitation tunnel model	Cussons K23
Test section dimensions	2300 nm, 630 nm, 350 mm
Maximum allowable propeller diameter	200 mm
Maximum water circulation velocity	3.6 m/s
Gauge pressure fluctuation	30-120 kPa
Dynamometer model	Cussons H29 Propeller Dynamometer
Propeller maximum revolution	3000 rpm
Maximum thrust and torque	400 N and 150 N.m

Table 1: K23 cavitation tunnel's specification.

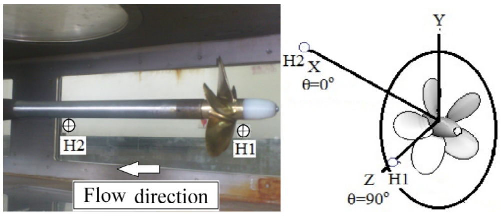

Figure 2: Position of H1 and H2.

Hydrophone	X (m)	Y (m)	Z (m)	θ (x-z)
H1	0	0	0.225	90°
H2	0.50	0	0.225	90°

Table 2: Coordinates of hydrophones and their applications in numerical and experimental method.

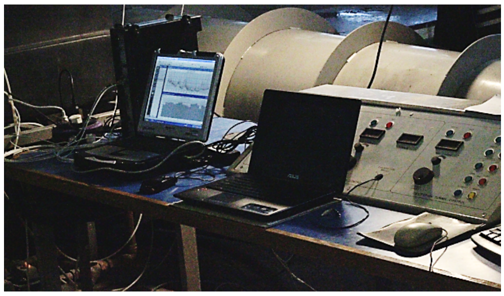

Figure 3: Test set up in noise measuring.

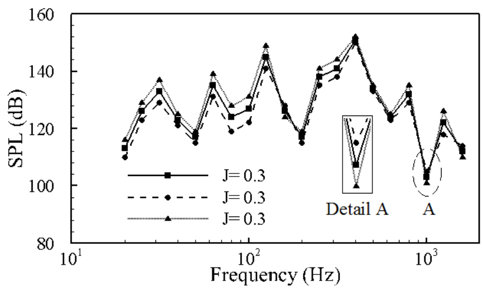

Figure 4: Results of three times measuring in cavitation tunnel for *J*=0.3.

The same test setup was considered for noise measurements according to the 18th ITTC cavitation committee recommendations [31]. In order to measure the propeller noise in K23 cavitation tunnel, two B & k 8103 hydrophones were used. The position of hydrophones is shown in Figure 2 and Table 2. The hydrophones were well fixed in two positions on Plexiglas section in the cavitation tunnel and at a vertical distance of 250 mm from the shaft centerline one 500 mm forward of the rotation plane of the propeller and the other in the rotation plane of the propeller. Measuring setup depicts in Figure 3. The following steps are carried out to extract net propeller noise:

- Measuring flow noise in cavitation tunnel when dynamometer is off.
- Measuring flow and dynamometer noise when the propeller is not installed in the cavitation tunnel.
- Measuring total noise in the tunnel when the propeller rotates.

For the above steps, each test is repeated three times and the uncertainty measurements have been obtained ±3dB. Figure 4 is depicted total Sound Pressure

Levels (SPLs) for J=0.3 for the three measurements in cavitation tunnel.

Model and Paint Application to the Propeller Blades

A five-blade propeller model with brass material is used which has D=0.15m and $A_E / A_o = 0.7$. Where, D and A_E / A_o are diameter and extended area ratio of the propeller, respectively. This model was designed at the CEHDMV and is a research model with the high application at the CEHDMV. Also, it has been a research propeller in a variety of hydrodynamic studies at the CEHDMV laboratory. However, previously no noise measurements had been done for this model.

Previous studies recommended that paint application to propeller blades be a 3-layer coating and applied in an appropriate laboratory condition carefully [22,23]. In this study, a 3-layer coating is applied which consist of an epoxy base, a tie coat and a silicone polymer (IS700) top coat, which are dried to the thickness of about 200 μm on the propeller surfaces. Propeller efficiency decreased when coating thickness increased more than 300 μm. Therefore, appropriate coating thickness is considered 200 μm for this model. The IS700 coating creates very smooth and hydrophobic surfaces. This coating is thin therefore area friction is very low. Its smoothing properties have impacts on propeller flow uniformity. This coating is applied to delay the transition from laminar to turbulent flow on propeller edge and tip and postpone the cavitation phenomenon. As mentioned, cavitation is the main source of noise in marine propellers. Figure 5 shows the model without and with the coating applied on the blades.

Results and Discussion

Hydrodynamics characteristics

To obtain the characteristic curves in the hydrodynamics tests, the propeller rotational speed was kept constant, and the water circulation flow was varied in the allowable range of cavitation tunnel, at 0-3.6 m/s. Also, the flow speed was kept constant and the rotational speed was varied in the range of 300-1600 rpm with repeated tests. The ambient pressure for non-cavitation conditions was kept constant, 100 kPa, in the cavitation tunnel. Figure 6 presents the thrust, torque and efficiency coefficients for the uncoated and coated propeller in cavitation tunnel. In this figure propeller advance coefficient, J, thrust coefficient, K_T, torque coefficient, K_Q, and open water efficiency, η_0 are defined as [18].

$$J = \frac{V}{nD}, K_T = \frac{T}{\rho n^2 D^4}, K_Q = \frac{Q}{\rho n^2 D^5}, \eta_0 = \frac{J}{2\pi}\frac{K_T}{K_Q} \quad (1)$$

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). Based on the present measurements, we can conclude that IS700 coating does not significantly effect on the thrust and torque characteristics of this propeller.

Cavitation inception and development tests

Two procedures are generated for cavitation inception and development conditions in the cavitation tunnel. In the first method, the flow velocity and ambient pressure are kept at 0.7 m/s and 90 kPa, respectively and then the propeller rotational speed is increased from 900 rpm to 1600 rpm. In the second method, the rotational speed of propeller and flow speed are fixed at N=1400 rpm and V=0.7 m/s, respectively and then the ambient pressure in the tunnel is decreased from 100 kPa to 70 kPa. With the reduction in ambient pressure, as it reaches the point where the pressure is less than vapor pressure in the corresponding temperature, the liquid water particles turn into cavity bubbles, this phenomenon is known as the cavitation. Cavitation inception is occurred at J=0.2 in uncoated propeller for N=1400 rpm and p=90 kPa while it happened at J=0.2, N=1400 rpm and p=85 kPa for coated propeller. The experimental investigation also indicates that cavitation phenomenon is extended by the pressure drop in the cavitation tunnel. The cavitation behavior of propellers can be represented by a cavitation parameter; the cavitation number is calculated using Equation (2) [18]:

$$\sigma = \frac{p - p_v}{\frac{1}{2}\rho(\pi n D)^2} \quad (2)$$

where D and n are the propeller diameter (m) and the propeller rotational speed (rad/s), respectively. ρ is the water density (kg/m^3). P and Pv are the ambient pressure (Pa) and water vapor pressure (Pa), respectively. The results of cavitation numbers, σ, at different

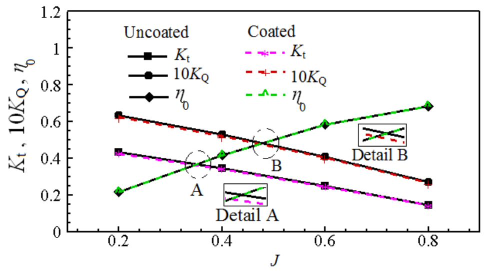

Figure 5: Open water curves for the uncoated and coated propeller.

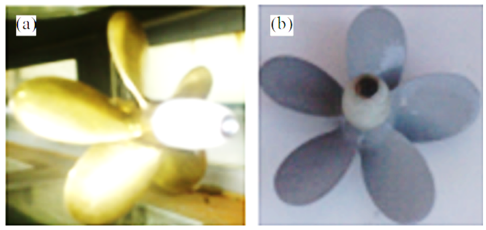

Figure 6: Model propeller with (a) uncoated and (b) coated blades.

J	*N* (rpm)	*p* (kPa)	*σ*	Cavitation inception (uncoated)	Cavitation inception (coated)
0.30	900	100	3.91	No	No
0.30	900	95	3.71	No	No
0.30	900	90	3.51	No	No
0.30	900	80	3.11	No	No
0.30	900	70	2.71	No	No
0.23	1200	90	1.97	No	No
0.23	1200	80	1.75	No	No
0.23	1200	70	1.52	No	No
0.20	1400	100	1.61	No	No
0.20	1400	90	1.45	yes	No
0.20	1400	85	1.39	yes (cavitation development)	yes
0.20	1400	80	1.28	yes (cavitation development)	yes (cavitation development)
0.17	1600	100	1.23	yes (cavitation development)	yes (cavitation development)
0.17	1600	90	1.11	yes (cavitation development)	yes (cavitation development)

Table 3: Operating conditions for cavitation inception and development in uncoated and coated propeller.

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operating conditions are presented in Table 3. As observed from this table, cavitation numbers in cavitation inception conditions are 1.45 and 1.39 for uncoated and coated propeller, respectively. Injecting and expanding the vapor volume fraction in the fluid increases the total noise because cavitation is one of the most important noise sources of the propeller. Therefore, it is important which cavitation delaying methods are considered in marine propellers. One of the best of these methods is using of FR coatings on blade surfaces of the marine propeller Figure 7.

Figure 7b shows that the cavitation initiated for constant rotational speed, N=1400 rpm, V=0.7 m/s and p=90 kPa in uncoated propeller. As observed in Figure 7c, with increasing in the rotational speed, sheet and tip cavitation increase in blade tip which is seen as a pale halation in experimental tests. Figure 8 shows that the cavitation inception occurred at J=0.2 and p=85 kPa for coated propeller. By comparison Figures 7b and 8b, it is concluded that the effect of coating on cavitation inception was significant in constant advance coefficient for

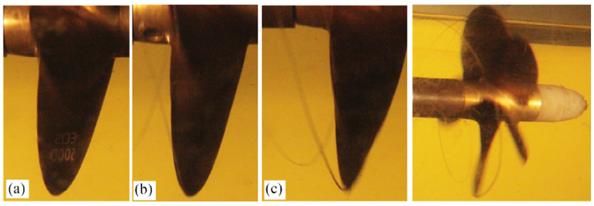

Figure 7: The development cavitation in uncoated propeller for (a) J=0.3 and p=90 kPa, (b) J=0.2 and p=90 kPa and (c) J=0.17 and p=90 kPa.

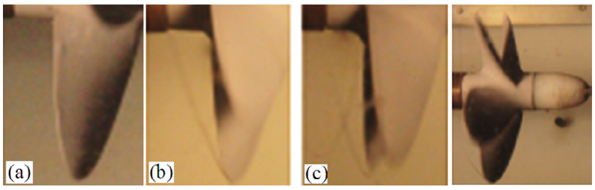

Figure 8: The development cavitation in coated propeller for (a) J=0.3 and p=90 kPa, (b) J=0.2 and p=85 kPa and (c) J=0.17 and p=90 kPa.

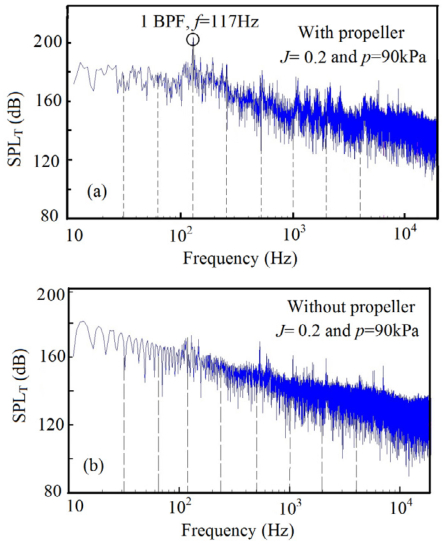

Figure 9: The non-processed spectrum (a) total noise and (b) background noise in cavitation tunnel for H1 in uncoated propeller (N=1400 rpm, V=0.7 m/s, p=90 kPa).

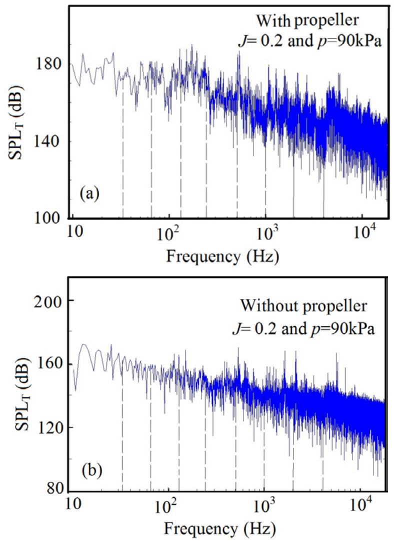

Figure 10: The non-processed spectrum (a) total noise and (b) background noise in cavitation tunnel for H2 in uncoated propeller (N=1400 rpm, V=0.7 m/s and p=90 kPa).

this propeller. Therefore, in constant advance coefficient and ambient pressure, cavitation inception is postponed for coated propeller whereas if ambient pressure decreases in cavitation tunnel from 90 kPa to 85 kPa then cavitation inception happens at J=0.2 for the coated propeller. On the other hand under the same conditions for uncoated and coated propellers, the uncoated propeller tip vortex was thicker while the extent of sheet cavitation was relatively large compared to the coated propeller. Therefore, IS700 coating has many effects on cavitation and makes cavitation inception postpone.

Noise measurements

The model scale measurements and procedures have been submitted to the ITTC committee and reported in the Specialist Committee on Hydrodynamic Noise for the 27th ITTC [32]. The total SPLs of the propeller at wideband are first recorded at frequencies ranging from 20 Hz to 20 kHz, which included both the total noise in tunnel (propeller noise, equipment vibration, dynamometer noise and circulation noise of flow), and the noise generated by the background noise. In order to calculate the noise generated in the tunnel, the background noise is measured separately and subtracted logarithmically from the total measured noise.

In this study, the results of net propeller noise are presented in 1/3-octave band for each center frequencies [33]. The measured values of total SPLs in each 1/3-octave band to an equivalent 1Hz bandwidth by means of the correction formula follow [22,23]:

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

Where, $SPLm$ and $SPLs$ are measured SPL at each center frequency and bandwidth for each 1/3-octave band filter in 1Hz, respectively. The net SPL (SPL_N) is calculated at each center frequency using Equation (4).

$$SPL_N = 10 \log [10^{(SPL_T/10)} - 10^{(SPL_B/10)}] \quad (4)$$

Here SPL_T and SPL_B are total and background $SPLs$, respectively, measured at an equivalent 1Hz bandwidth and 1m. Time history signals are transformed to the frequency domain using Fast Fourier Transform (FFT) utility in Matlab code. Figures 9 and 10 for hydrophones 1 and 2 are depicted an example of the noise spectrum in the wide band of

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the frequency range for total and background noise in the cavitation tunnel. Figures 9 and 10 are presented for *N*=1400 rpm, *V*=0.7 m/s and *p*=90 kPa in the uncoated propeller. The frequency wide band for other operational conditions is not presented here. The experimental results for SPLs of the two hydrophones 1 and 2 in the constant pressure, 90 kPa, three rotational speeds *N*=900, 1400, 1600 rpm and constant flow speed, *V*=0.7 m/s, are shown in Figures 11 and 12. The total SPLs under non-cavitation (*J*=0.3), cavitation inception (*J*=0.2) and development conditions (*J*=0.17) for hydrophones 1 and 2 are presented in Figures 11 and 12 for uncoated and coated propeller. As seen in these figures, the total SPLs rise with the increasing in rotational speed of the propeller. Also, propeller noise is significantly decreased between 2 to 5 dB in coated propeller. The difference between total SPLs in non-cavitation and cavitation inception conditions are approximately in the range 5 to 20 dB in each frequency for both uncoated and coated propeller which is related to increase of propeller rotational speed from 900 to 1400 rpm. In comparison total SPLs under cavitation development condition with two other conditions, the difference between the total SPL is in range 10 to 30 dB for both uncoated and coated propeller.

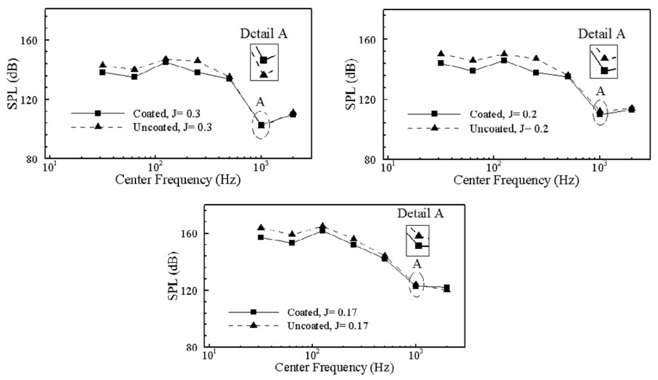

Figure 11: The SPLs results for H1 in (a) *N*=900 rpm, (b) *N*=1400 and (c) *N*=1600 rpm.

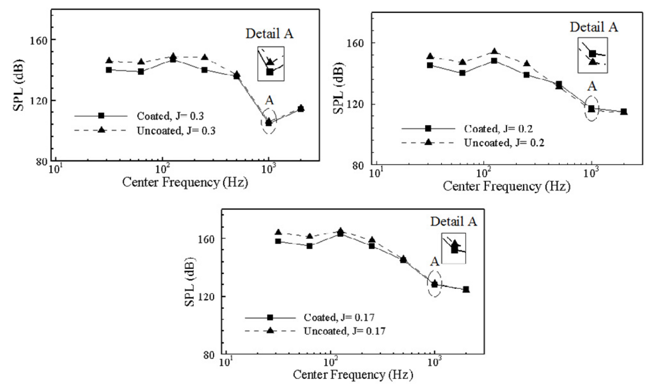

Figure 12: The SPLs results for H2 in (a) *N*=900 rpm, (b) *N*=1400 and (c) *N*=1600 rpm.

As far as the effect of IS700 coating on the noise levels was concerned the noise levels of coated blades were less than those of the uncoated blades at the advance coefficients of *J*=0.30 ~ 0.17, (Figures 11 and 120. The cavitation on the uncoated blades occurred earlier than the coated blades as shown by Figures 7b and 8b. Cavitation started at *J*=0.2 and *p*=90 kPa for uncoated propeller while it occurred at *J*=0.2 and *p*=85 kPa for coated propeller. Also, as observed from Figures 7b and 8b, tip vortex is thicker for uncoated propeller than coated propeller. Cavitation development and its state have an important impact on increasing noise levels. Coating reduced the total noise levels at the low advance coefficients for this propeller. Tables 4 and 5 present difference between SPLs in uncoated and coated propeller in *J*=0.3, 02 and 0.17 for hydrophones 1 and 2, respectively.

We have used IS700 coating and thus cavitation is postponed and the propeller noise is decreased. The IS700 coating has more effects on reducing propeller noise than the coatings used in previous works.

Conclusion

An experimental study was carried out to investigate the effects of FR coating (IS700) on the cavitation and noise characteristics of a five-blade propeller model in non-cavitation, cavitation inception and development conditions. In this paper, cavitation inception and development conditions are studied for a five-blade propeller by an experimental method in cavitation tunnel. Also, propeller noise is

f_0 (Hz)	*SPL* (dB), *J*= 0.3		Δ*SPL* (dB)	*SPL* (dB), *J*= 0.2		Δ*SPL* (dB)	*SPL* (dB), *J*= 0.17		Δ*SPL* (dB)
	Uncoated	Coated		Uncoated	Coated		Uncoated	Coated	
31.5	143	138	5	150	144	6	164	157	7
63	140	135	5	146	139	7	159	153	6
125	147	145	2	150	146	4	165	162	3
250	146	138	8	147	138	9	156	152	4
500	135	134	1	136	135	1	144	142	2
1000	102	103	1	112	110	2	124	123	1
2000	111	110	1	114	113	1	120	122	2

Table 4: Difference between SPLs for uncoated and coated propeller in H1.

f_0 (Hz)	*SPL* (dB), *J*= 0.3		Δ*SPL* (dB)	*SPL* (dB), *J*= 0.2		Δ*SPL* (dB)	*SPL* (dB), *J*= 0.17		Δ*SPL* (dB)
	Uncoated	Coated		Uncoated	Coated		Uncoated	Coated	
31.5	146	140	6	151	145	6	164	158	6
63	145	139	6	147	140	7	161	155	6
125	149	147	2	154	148	6	165	163	2
250	148	140	8	146	139	7	159	155	4
500	137	136	1	131	133	2	146	145	1
1000	106	105	1	116	117	2	129	128	1
2000	115	114	1	114	115	1	124	125	1

Table 5: Difference between SPLs for uncoated and coated propeller in H2.

measured and presented in different operating conditions for uncoated and coated propeller.

Up to now, few studies have considered the effect of FR coating on the propeller cavitation and noise. In the present research, the effect of IS700 coating on cavitation and noise was investigated for the first time on a propeller. Also in previous studies, the effect of coatings used was not effective on cavitation inception while the coating used in the present work has a significant effect on cavitation inception and noise reduction. Cavitation inception occurred at J=0.2 in uncoated and coated propeller while ambient pressure was selected in 90 kPa and 85 kPa for uncoated and coated propeller in the cavitation tunnel, respectively. The form and extent of the inception and development of cavitation patterns, which were mainly tip vortex and sheet cavitation, were somehow different such that the uncoated propeller tip vortex was thicker while the extent of sheet cavitation was relatively large compared to the coated propeller. The main innovation and motivation of this investigation is to consider of IS700 coating effects on the hydrodynamic, cavitation inception and development characteristics and noise reduction of a five-blade propeller. The effect of IS700 coating was significant on noise reduction in low-frequency range specifically. The noise was reduced between 2 -5 dB for coated propeller. The IS700 coating effect on the noise reduction is less in fully developed cavitation than cavitation inception and non-cavitation status.

It is recommended that the IS700 coating to be used on the marine propeller in order to delay cavitation inception and reduced noise.

Appendix: Math Notation List

D: The diameter of propeller (m); Fc: Center frequency (Hz); Δf: Bandwidth for each one-third octave band filter in Hz (Hz); J: V/nD: Advance coefficient; KQ: Q/ρn2D5 Torque coefficient; Kt: T/ρn2D4 Trust coefficient; n: Rotational speed; P_0: Atmosphere pressure (pa); Pv: Vapor pressure (pa); Pa: Static pressure (pa); Q: Torque (Nm); R: Radius of propeller (m); SPLs: Sound pressure level; SPLb: Background sound pressure level measured at an equivalent 1 Hz bandwidth and 1 m (in dB; re 1 mPa); SPLd: Net sound pressure level of propeller for free-field; SPLm: Measured sound pressure level at each centre frequency (in dB; re 1 mPa); SPLn: Net sound pressure level calculated at equivalent 1 Hz bandwidth and 1 m(in dB; re 1 mPa); SPLt: Total sound pressure level measured at an equivalent 1 Hz bandwidth and 1 m (in dB; re 1 mPa); T: Trust (N); η0: Efficiency; θ: Angle between x-z axes in propeller (deg); Ϭ: Cavitation number.

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