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Effects of Changes in Hub Geometry on the Performance of Podded Propellers in Cavitating and Non-Cavitating Open Water Conditions

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ABSTRACT

There are several possible explanations for the difference in performance of puller and pusher type podded propulsors. One is related to the difference in the hub geometry (hub taper angle). Puller and pusher propellers have opposite hub taper angles, hence different hub and blade root shapes. Results are presented here of an experimental study focused on the variation in performance of pusher and puller propellers with the same blade sections, but different hub taper angles, both in cavitating and non-cavitating open water conditions. In the first phase of the study, three model propellers with different hub taper angles were tested in open water conditions. In the second phase, a similar study was carried out in a cavitation tunnel. Both of the studies were done to investigate the effect of hub taper angle on performance at different operating conditions. The open water propeller data is used to provide a comparison with the cavitation performance. From the open water study, it is concluded that hub taper angle has a significant effect on propulsive performance, especially at the highly loaded condition, where the puller propellers perform better than the pusher ones. From the cavitation tunnel study, it is concluded that the puller configuration propellers do not have better performance than the pusher configuration propellers under all cavitating conditions.

1. INTRODUCTION

A research program on podded propellers is being undertaken jointly by the Ocean Engineering Research Centre (OERC) at Memorial University, the National Research Council's Institute for Ocean Technology (IOT), Oceanic Consulting, and Thordon Bearings. The program combines developments in numerical prediction methods with parallel developments in experimental apparatus. Amongst the hydrodynamic issues that have been identified are questions regarding the effects of hub taper angle, pod-strut interactions, gap pressure, and pod-strut geometry on podded propeller performance. Work is also being done on extrapolation of powering for ships with pods. Some fundamental investigations are required to fill these research gaps.

In a podded propulsion system, a propeller is attached to one or both ends of a pod shell. A motor inside the pod drives the propeller through a short shaft. The pod unit is connected to the ship's hull through a strut and slewing bearing assembly. This assembly allows the entire pod unit to rotate and thus the thrust developed by the propeller(s) can be directed anywhere over a horizontal plane over 360°. This eliminates the need for a rudder and additional appendages, such as shaft brackets as used in conventional propulsion systems [1]. A general arrangement showing the major components of two podded propulsion systems and a conventional propeller-rudder propulsion system is provided in figure 1.

Two types of podded propulsion systems are mainly used in the marine industry, namely, pusher and puller types (figure 1). Currently, more commercial vessels are equipped with puller systems. It is known from shipbuilders that pusher propellers yield a lower thrust and hence worse hydrodynamic efficiency compared to puller ones. A numerical study was performed to investigate why this is so [1]. In the

study it was shown how pusher and puller propellers have opposite hub taper angle (see figure 2), hence different blade root sections, and how this change affects the performance.
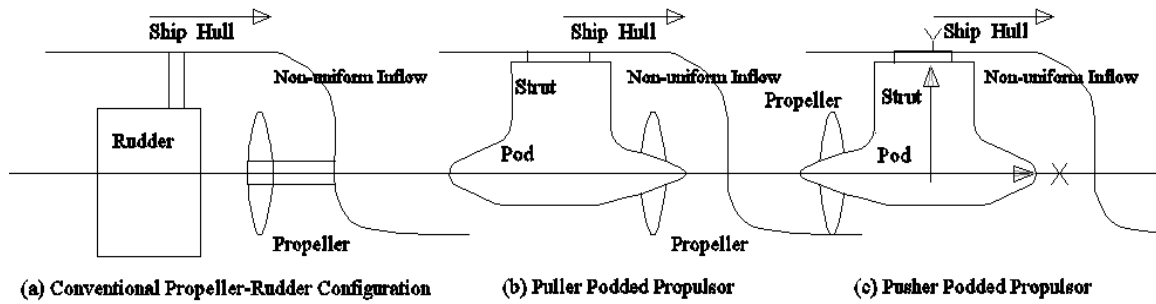

Figure 1. Major components of two podded propulsion systems and a conventional propulsion system.

The occurrence of cavitation on marine propellers causes undesirable effects such as radiated noise, structural vibration, blade surface erosion and deterioration of performance. The propellers used in a podded propulsion system are vulnerable to various kinds of cavitation, which may be different when compared to a conventional propeller-rudder propulsion system. The flow conditions of a pusher and a puller propeller are different, which induces different cavitation characteristics.
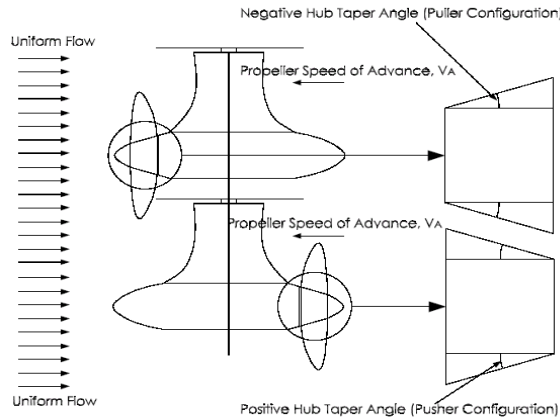

Figure 2. Podded Propulsion System: puller and pusher systems; definition of hub taper angle.

It is useful to perform a comparative study of a puller and a pusher podded propeller at several cavitating and non-cavitating open water conditions. This will help in judging the relative performance variation of these two propellers and if there is a superiority of one over the other. The current experimental study was carried out to fill this knowledge gap in understanding the hydrodynamics of podded propellers. The open water tests involved measurements of the performance of three bare propellers with different hub taper angles under several open water conditions. The cavitation tunnel tests involved measurements of the performance of four bare propellers with different hub taper angles under several cavitating conditions. In all of the studies the bare propellers were tested without any pod-strut bodies attached to them, the target being the study of effect of hub taper angle. The details of the propeller design and model propellers are given in section 2. Section 3 details the experimental set-up and test conditions for both open water and cavitating conditions. In section 4 all the experimental results and relevant discussions for the performance of the propellers are provided Finally, in section 5 some concluding remarks are provided based on the experimental results and analyses.

2. MODEL PROPELLERS

The four model propellers under investigation have the same blade sections with different hub taper angles. The basic geometrical particulars of the propellers are given in table 1. In [2] details are given of the model propellers' geometries. The four propellers have hub taper angles of 15° (**Push+15**), 20° (**Push+20**), -15° (**Pull-15**), -20° (**Pull-20**). Figure 3 shows a photograph of the model propellers.

Table 1: Basic geometry of the model propeller.

| Diameter (m)	0.27	No. of Blades	4
Design adv. Coeff., J		0.8	
Hub-Diameter (H/D) ratio		0.26 (based on regular straight hub)	
Section thickness form		NACA 66 (DTMB Modified [3])	
Section meanline		NACA = 0.8	
Blade planform shape		Blade planform shape was based on David Taylor Model Basin model P4119 [3]	
Expanded area ratio, EAR		0.60	
Pitch distribution		Constant, P/D=1.0	
Skew Dist.	Zero	Rake Dist.	Zero

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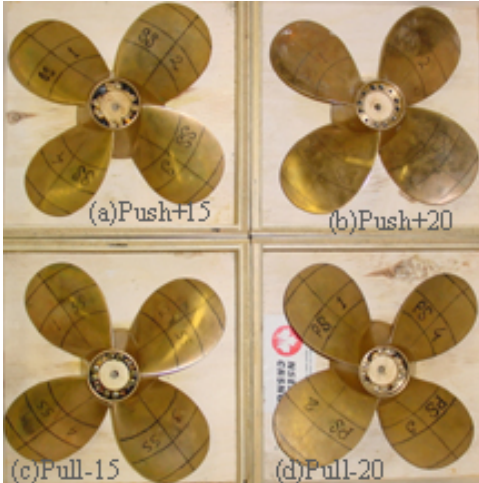
Figure 3. Four model propellers: (a), (b), (c), (d) are the propellers with hub taper angles of +15° (push), +20° (pull), -15° (pull), -20° (pull), respectively.

3. EXPERIMENTAL SET UP AND TEST CONDITIONS

The experiments in open water conditions were conducted in the towing tank facility at the Institute for Ocean Technology (IOT) using the Kempf & Remmers Dynamometer depicted in Figure 4 below. This instrumentation package allows for the measurement of propeller thrust and torque data over a range of advance coefficients.

When testing a pusher mode, conical hub propeller in the open water condition, it is necessary to use a large, bulbous nose cone to provide suitable inflow conditions to the propeller. These nose cone adapters, illustrated in Figure 5 below, were designed in accordance with the applicable ITTC guidelines [4] for open water tests and podded propellers.

Figure 4. Kempf & Remmers dynamometer: in test frame (left) and in the tow tank (right).
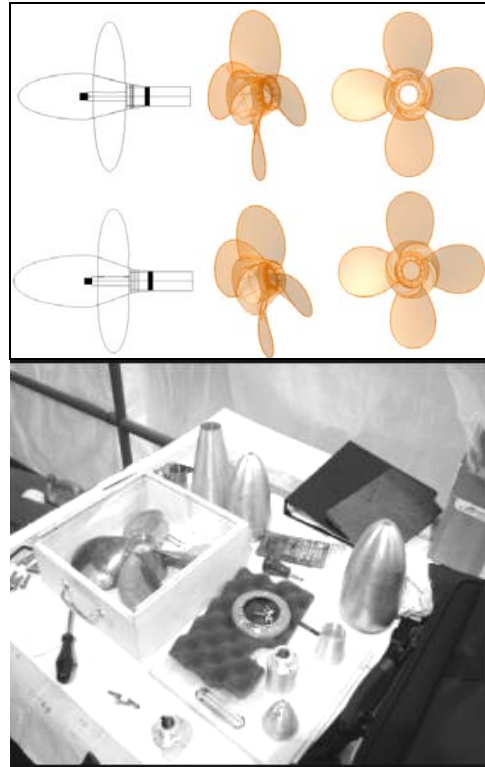

Figure 5. Solid model for the propellers and nose cone adapters for Push+15 (1st row) and Push+20 (2nd row); Pictures of nose and rear cone adapters for the propellers.

The operating rotational speed used for these experiments was selected based on data collected from a preliminary set of experiments to look for viscous effects [2]. These were conducted by measuring thrust and torque at specific J values over a range of rotational speeds to ensure the propeller was producing consistent results. The final selected rotational speed used in these tests was 15 rps.

The experiments under cavitation conditions were carried out at the Institute of Ocean technology (IOT) cavitation tunnel facility. Doucet [5] detailed the tunnel configuration. Four model propellers were tested at nine cavitation numbers including the cavitation number at atmospheric pressure. For each set up, the propeller rotational speed and the static pressure in the measuring sections were maintained constant while thrust, torque and water speed were measured over a range of advance coefficients, J. The test matrix for both categories of tests is given in table 2.

In establishing the test conditions in table 2, the formulation used in [6] was used to calculate σ_n (equation 3.1).

$$\sigma_n = \left(P_{amb} + \rho gh - P_V\right)/\left(\frac{1}{2}\rho n^2 D^2\right) \dots \text{(3.1)}$$

where, P_{amb} is the ambient pressure on the fluid surface in Pa or N/m^2, ρ is the density of the fluid in kg/m^3, g is gravitational acceleration, taken as 9.81 m/s^2 and h is the immersion depth of the propeller centre in m. P_V is the saturated vapor pressure in Pa, Variable n is the angular speed of the propeller in rad/s and D is the diameter of the propeller in m.

Table 2: Summary of test conditions in cavitating and non-cavitating open water conditions

	Item	Test Points
Cavitating Conditions	No. of propellers	4 (Hub taper angle 15°, 20°, -15° and –20°)
	Cavitation Numbers, σ_n	0.6, 0.8, 1.0, 1.2, 1.6, 2.0, 3.0 (σ_{design}), 4.5, 7.38 (σ_{atm})
	Propeller rps	25
	Water Speed, V_W, (m/s)	2.0~8.5 (as the tunnel restrictions allow)
Open Water conditions	No. of propellers	3 (Hub taper angle 15°, 20°, -15°)
	Propeller rps	15
	Water Speed, V_W, (m/s)	0.0~5.00, at least 15 test points

A rotational speed of 25 rps was used in order to get low cavitation numbers below 1.0 (see equation 3.1). Video footage for all experimental conditions was taken. Later, photographs were extracted from the video clips at different operating conditions at all cavitation numbers. The air content number, α/α_s [7] during the experiments varied from 0.2 to 0.4. The propellers were mounted on the upstream shaft with an axially uniform inflow. While doing the tests, the tunnel static pressure and propeller rotation speed were fixed based on the required cavitation number. After the tunnel flow was stabilized, the flow speed was changed gradually to get the required advance coefficients, keeping the rotational speed fixed. Propeller thrust and torque were measured at each operating condition.

4. RESULTS AND DISCUSSION

4.1 Effect of hub taper angle on performance in open water conditions

The experimental results for the two propellers were collected and analyzed in terms of propeller thrust coefficient, K_T, propeller torque coefficient, $10K_Q$, propulsive efficiency, η and propeller advance coefficient, J. K_T, K_Q, η and J are defined in equations 4.1-4.4, respectively.

$$K_T = T /\left(\rho n^2 D^4\right) \dots \text{(4.1)}$$

$$K_Q = Q /\left(\rho n^2 D^5\right) \dots \text{(4.2)}$$

$$\eta = \left(J /(2\pi)\right) \times \left(K_T / K_Q\right) \dots \text{(4.3)}$$

$$J = V_A /(nD) \dots \text{(4.4)}$$

where, T is the thrust produced by the propeller in N, Q is the torque consumed by the propeller in N-m, ρ is the water density in Kg/m^3 and V_A is propeller speed of advance in m/s.

In Figures 6 and 7 the comparisons of the open water experimental results for the propellers with taper angles of 15° with -15° and 15° with 20°, respectively are shown. It is seen that hub taper angle has more effect on performance at highly loaded conditions than lightly loaded conditions.
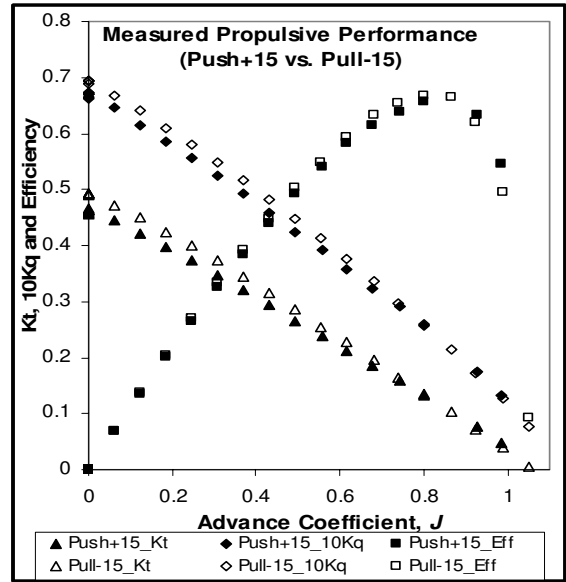

Figure 6: Experimental results showing the effects of hub taper angle on the propulsive performance of propellers with hub taper angles of 15° and –15°.

Quantitatively, in the bollard pull condition (zero advance coefficient) a decrease of 3.5% in thrust coefficient and 3.2% in torque coefficient were predicted for the pusher configuration propeller (Push+15°) as compared to the puller configuration propeller (Pull-15°). Again, in the bollard pull condition increases of 1.2% in thrust coefficient and 2% in torque coefficient were predicted for the Push+15° propeller as compared to the Push+20° propeller. An increase in propulsive performance for a propeller with negative hub taper angle, and a reduction in propulsive performance for a propeller with positive taper angle occurs may be attributed to two reasons. First is the change in leading and

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trailing edge area in the tapered hub propellers and second is the change in root section camber due to the conical hub surface.
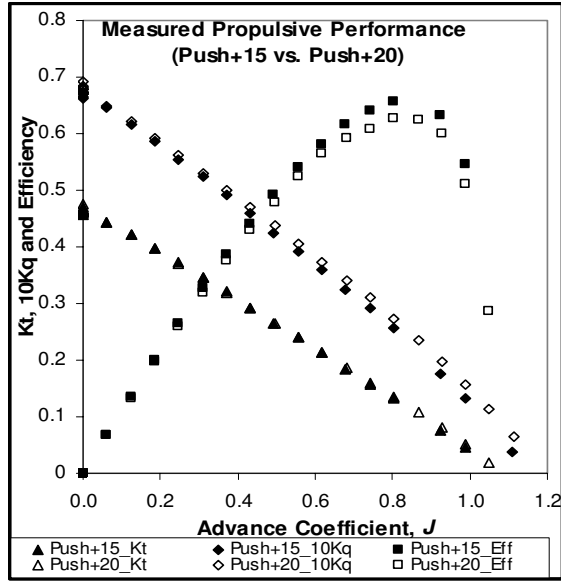

Figure 7: Experimental results showing the effects of hub taper angle on the propulsive performance of propellers with hub taper angles of 15° and 20°.

A comparison of performance of the propeller Pull-15° and Push+20° as compared to that of the propeller Push+15° is shown in table 3. All values in the table are in percentages and a negative sign indicates that the performance of the labeled propeller is better than that of the Push+15° propeller and vice versa. It is shown that the puller propeller performs better at high and moderate loading conditions, but at lightly loaded condition (J>=1.0) the pusher propeller performance is better. Again the propeller with higher hub taper angle (Push+20) performs similarly (slightly better) to that of the propeller Push+15.

Table 3 Comparison of propulsive performance of the three model propellers.

	J	**%Kt**	**%10Kq**	**%Efficiency**
Pull-15	0.00	6.58	3.56	0.00
	0.20	5.79	3.62	0.82
	0.40	4.96	3.75	1.28
	0.60	3.24	2.52	1.84
	0.80	0.87	0.54	1.58
	1.00	-1.47	-1.02	-9.48
	J	**%Kt**	**%10Kq**	**%Efficiency**
Push+20	0.00	-0.97	-0.62	0.00
	0.20	-0.2	-0.37	0.17
	0.40	0.23	-0.65	0.87
	0.60	-0.01	-1.89	1.85
	0.80	-2.24	-5.5	3.10
	1.00	-0.97	-0.62	0.00

4.2 Taper Angle Effects on Performance Under Cavitation

The effect of hub taper angle on propulsive performance under cavitation can be studied by analyzing the results in terms of K_T, K_Q and J for different σ_n. Comparison of the performance of two propellers having the same blade section but opposite hub taper angles reveals the effect of hub taper angle on performance. Figures 8(a) through 8(h) provide such comparisons (Push+15° and Pull-15°). In each figure the performance of the two propellers at atmospheric pressure is also included together with the photographs showing back cavitation at specified operating conditions of the pusher (left picture) and puller (right picture) propellers. It is seen from these figures that the propeller used in a puller podded system (Pull-15°) produces higher thrust and torque for all cavitation numbers tested and almost the entire range of advance coefficient, J. Exceptions can be seen at very low cavitation numbers (σ_n=0.6) at high advance coefficient (J>0.70). For this condition the puller and the pusher propellers perform almost equally.
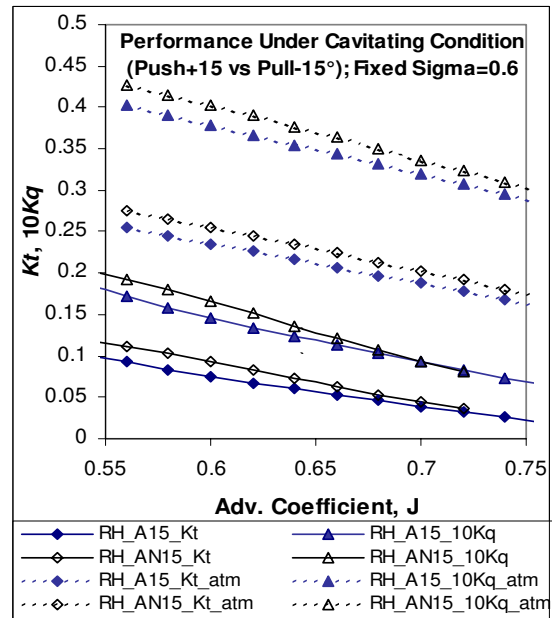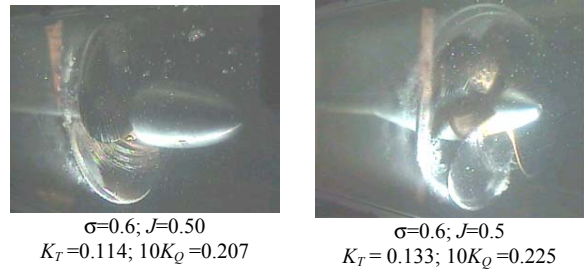

σ=0.6; J=0.50
K_T =0.114; $10K_Q$ =0.207

σ=0.6; J=0.5
K_T = 0.133; $10K_Q$ =0.225

Figure 8 (a). Comparison of K_T and K_Q of the Push+15° and the pull-15° propellers at σ=0.6.

σ=1.0; *J*=0.50
K_T =0.201; $10K_Q$ =0.348
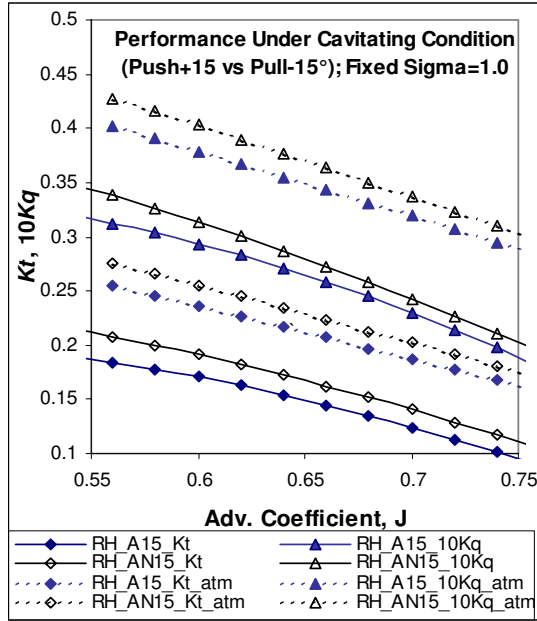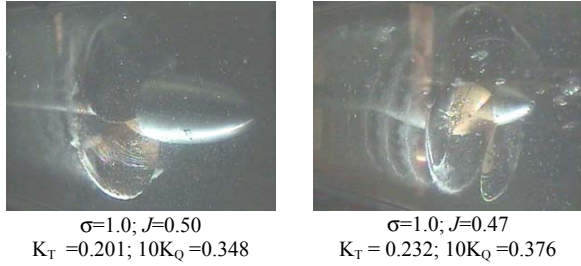

σ=1.0; *J*=0.47
K_T = 0.232; $10K_Q$ =0.376

Figure 8 (b). Comparison of K_T and K_Q of the Push+15° and the pull-15° propellers at σ=1.0.

The appearance of the cavitation patterns for the two propellers at selected cavitation numbers is presented. The test conditions together with the quantitative performance are presented with each picture. The patterns are self-explanatory and detailed discussion of all the patterns is out of the scope of the paper. The cavitation patterns at low *J* values varied from steady sheet cavitation on the whole surface of the blade suction side at the lowest tested cavitation number (σ_n=0.6), to steady/unsteady sheet cavitation with unsteady streak cavitation on a portion of the blade surface accompanied by thick tip vortex cavitation at moderate cavitation number (σ_n=1.0~2.0), to thin tip vortex cavitation at atmospheric pressure. All of the propellers show the similar cavitation patterns at the similar operating conditions.

It should be noted here that the four propellers have the same design blade sections and only differ in their hub taper angle. The blade section near the hub changes because of the solid body interaction of blade and hub. This change is responsible for the change of flow pattern around the blade root and hence the local cavitation characteristics. The

cavitation types that most influence the performance are tip vortex and sheet. The patterns of these two types are similar for the propellers. Hence the cavitation characteristics of the bare propellers do not change much at different operating conditions. The cavitation characteristics of the two propellers around the hub and blade roots were expected to vary but it was not observed. In reality, a pusher propeller operates in the strut wake, hence expected to show more unsteady cavitation characteristics than a puller propeller.
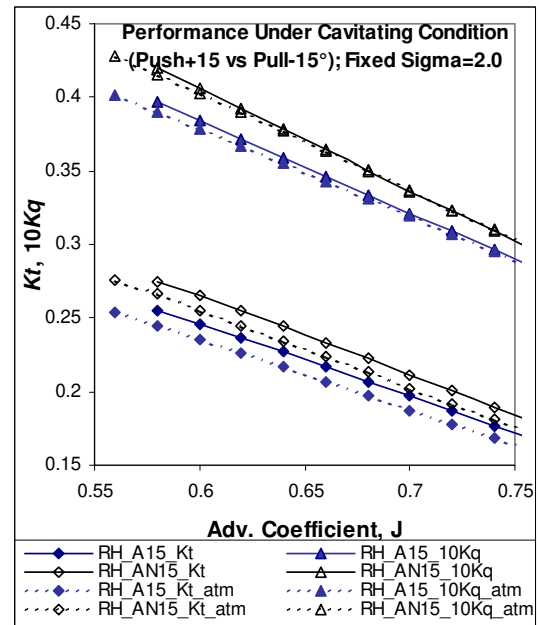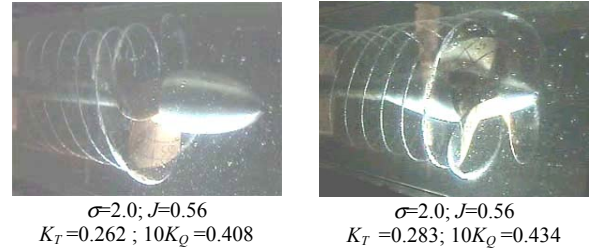

σ=2.0; *J*=0.56
K_T =0.262 ; $10K_Q$ =0.408

σ=2.0; *J*=0.56
K_T =0.283; $10K_Q$ =0.434

Figure 8 (c). Comparison of K_T and K_Q of the Push+15° and the pull-15° propellers at σ=2.0.

Table 4 provides a quantitative analysis of performance variations of the two propellers operating under three cavitation numbers as compared to the performance at atmospheric pressure (equivalent to the open water condition). The percentage increase or decrease of K_T and η is indicated by a + or - sign, respectively. The amount of thrust loss for the Pull-15 propeller is almost the same or less than that of the Push+15 propeller at lower cavitation numbers as compared to the thrust produced at atmospheric pressure operating condition. For example, for the Pull-15 propeller at σ_n =0.6, a decrease of 58% in K_T and 11% in η

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occurred at J=0.54 (as compared to the same operating condition at atmospheric pressure) whereas, for the Push+15 propeller, the corresponding decreases were 61% and 14%, respectively. For the Pull-15 propeller, at σ_n =1.0, a decrease of 46% in K_T and 9% in η occurred at J=0.80 (design) whereas, for the Push+15 propeller, the corresponding decreases were 54% and 16%, respectively. Again, for the Pull-15 propeller, at σ_{design} =3.0, an increase of 3% in K_T and 3% in η occurred at J=0.80 (design) similar to the Push+15 propeller. This analysis indicates that the percentage decrease of the K_T and η at low cavitation number with respect to the performance at the atmospheric pressure are close for the pusher and puller propellers under investigation. In other words, pusher and puller propellers with 15° hub taper angle perform equally under cavitation. The differences in performance that existed in open water operation remain the same while operating under cavitation too.
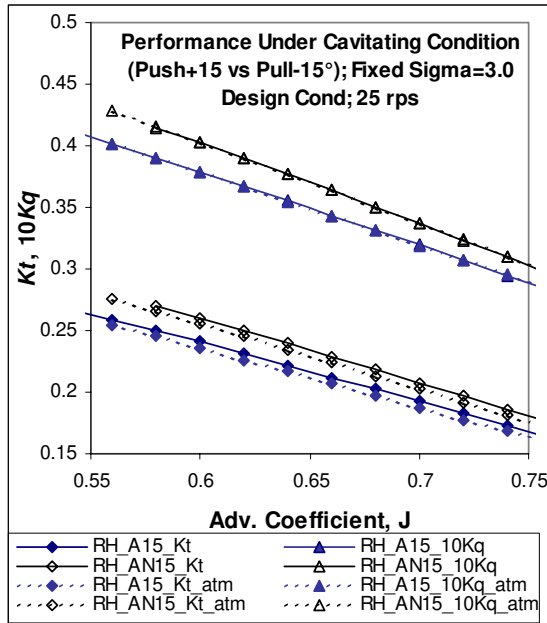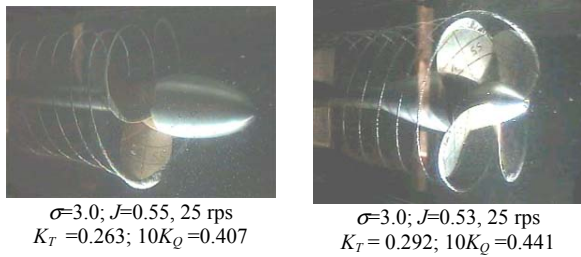

σ=3.0; J=0.55, 25 rps
K_T =0.263; 10K_Q =0.407

σ=3.0; J=0.53, 25 rps
K_T = 0.292; 10K_Q =0.441

Figure 8 (d). Comparison of K_T and K_Q of the Push+15° and the pull-15° propellers at σ=3.0.

Table 4. Change of K_T and η for the propellers, Push+15 and Pull-15 operating at three cavitation numbers (σ_v=0.6, 1.0 and 3.0) as compared to the corresponding K_T and η at atmospheric pressure condition (σ_{atm}=7.38).

J	Push+15					
	σ=0.6		σ=1.0		σ_{design} =3.0	
	% Change in K_T and K_Q based on					
	K_T	η	K_T	η	K_T	η
0.54	-61.6	-14.5	-27.7	-6.8	1.6	1.9
0.68	-76.8	-25.0	-31.5	-7.5	2.6	2.5
0.8	-96.6	-79.7	-54.1	-16.5	3.1	3.3
0.9	-	-	-92.8	-73.4	3.4	4.1
J	Pull-15					
	σ=0.6		σ=1.0		σ_{design} =3.0	
	% Change in K_T and η based on					
	K_T	η	K_T	η	K_T	η
0.54	-58.4	-10.7	-24.9	-5.3	0.9	1.6
0.68	-75.0	-17.8	-28.9	-3.4	2.5	2.5
0.8	-	-	-46.2	-9.1	2.9	3.0
0.9	-	-	-85.1	-49.4	3.1	3.3

Figure 9 shows the effect of taper angle on K_T as the cavitation number increases at three fixed advance coefficients. The figure shows that for all the cavitation numbers, the difference in K_T for the Pull-15° and Push+15° propellers remains almost same for the three J values. This means the performance of the two propellers does not change under cavitation.
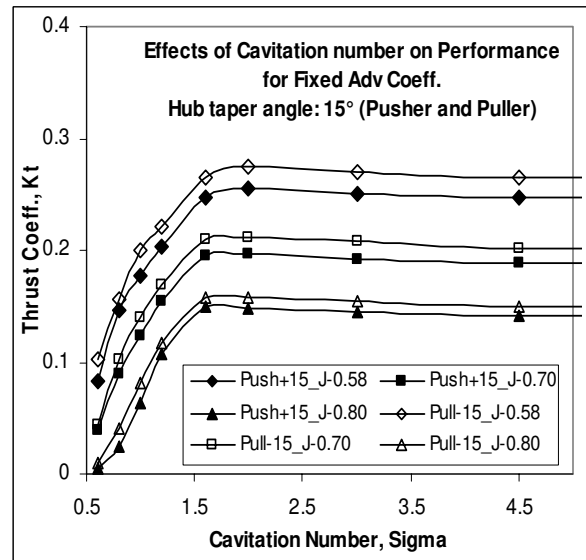

Figure 9: Comparison of performance (Push+15° and Pull-15°) variation with cavitation number for fixed advance coefficients.

5. CONCLUDING REMARKS

This research work aimed to compare the propulsive performance of a puller and pusher propeller at different cavitating and non-cavitating open water conditions. Both categories of tests revealed the effect of hub taper angle on the propellers' performance. The following conclusions were reached from the analyses of the data acquired.

From the open water test results, it is revealed that hub taper angle has an influence on the propulsive performance of a marine screw propeller. The influence is more noticeable for highly loaded conditions than for lightly loaded conditions. In the bollard pull condition, an increase of approximately 7% in thrust coefficient and 4% in torque coefficient were measured for the puller configuration compared to the pusher configuration with hub taper angles of $+15°$ and $-15°$, respectively. Again, at J=1.0 (very lightly loaded condition), a decrease of approximately 2% in thrust coefficient and 1% in torque coefficient were measured for the puller configuration compared to the pusher configuration. These variations in thrust and torque should be considered while designing propellers for different pod configurations.

In the cavitation tunnel tests, it was found that for each of the four propellers, the values of K_T and K_Q tend to increase as the cavitation number, σ_n, is increased from 0.6 to 1.6. As the cavitation number increased further, the values of K_T and K_Q decreased before they started to stabilize at the design cavitation number of (σ_{design}=3.0). It is also clear from the video footage/observation that the amount of cavitation on blade surface increased as the cavitation number decreased. All of the propellers showed similar cavitation patterns at the same operating conditions.

The difference in K_T, K_Q and η values between the Push+15 and Pull-15 propellers remained the same at all cavitation numbers for the entire range of advance coefficients. The difference is almost equal to the difference that exists in open water conditions. This means the changes in the performance of the pusher and the puller propellers in cavitation conditions are almost the same as each other as in open water conditions.

The open water experimental study revealed that the puller propeller performs better than a pusher propeller. The cavitation condition study revealed that the puller propeller with moderate hub taper angle performs equally as the pusher ones for all cavitation conditions tested.

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