STUDY ON PROPULSIVE PERFORMANCE OF TWO GEOMETRICALLY SIMILAR PODDED PROPULSORS

M Islam, Oceanic Consulting Corporation, Canada, **A Akinturk,** Memorial University of Newfoundland, Canada, **B Veitch**, Memorial University of Newfoundland, Canada, **Pengfei Liu,** Ocean Coastal and River Engineering (OCRE), National Research Council, Canada

SUMMARY

This paper presents the outcome of a research to evaluate the effect of size on the propulsive performance of podded propulsors in cavitating and non-cavitating open water conditions. Two cases are examined, namely: propeller-only case and pod-unit case. In the propeller-only case, a commercial propeller dynamometer is used to measure the thrust and torque of two propellers of different size at the four quadrants of propellers with varied shaft and flow speeds. Also, both propellers are tested at different tunnel pressure to study and compare the behaviour under similar cavitation conditions. In the pod-unit case, two geometrically similar but different sized pod-units are tested using two separate custom-made pod dynamometer systems in two towing tank facilities in straight-ahead and static azimuthing conditions. The study showed that the performance characteristics stabilize at lower *Reynolds Number* for the smaller propeller than the larger propeller. The propulsive performance of the two propellers was comparable in the four-quadrant experiments. Also, the experiments at the cavitating conditions showed that the cavitation characteristics of the two propellers were consistent at corresponding operating conditions. The experiment results of the two pod-units were also comparable for forces and moments in the three coordinate directions in the straight-ahead and static azimuthing conditions. A brief discussion on the uncertainty assessments for each of the measurements is also presented.

NOMENCLATURE

R_N	*Reynolds Number* (-)
υ	Kinematic viscosity (N s m^{-2})
D	Propeller Diameter (m)
P/D	Pitch-Diameter Ratio (-)
ρ	Density of water (kg m^{-3})
P	Pressure (N m^{-2})
T_{Prop}	Propeller thrust (N)
T_{Unit}	Pod unit thrust (N)
Q	Propeller torque (Nm)
V_A	propeller advance speed, in the direction of carriage motion (m s^{-1})
K_{TProp}	Propeller thrust coefficient (-)
K_{TUnit}	Pod unit thrust coefficient (-)
$10K_Q$	Propeller torque coefficient (-)
J	Propeller advance coefficient (-)
η_{Prop}	Propeller efficiency (-)
η_{Unit}	Pod unit efficiency (-)
K_{FZ}	Transverse force coefficient (-)
K_{FZ}	Vertical force coefficient (-)
K_{MX}	Moment coefficient around x axis (-)
K_{MY}	Moment coefficient around y axis (-)
K_{MZ}	Pod steering moment (-)

1. INTRODUCTION

It is essential in any physical model experimentation that the flow condition over the model body resembles to the corresponding prototype condition to ensure accuracy of the results when extrapolated to a larger scale. The *Reynolds Number* should be high enough to ensure the flow similarity. Through open-water experimentation, researchers have found that the propeller performance becomes independent of the *Reynolds Number* at a level where the laminar flow develops into turbulent flow. This limit can be found by completing the *Reynolds Number* Scale Effect experiments [1]. In such experiments, a model propeller is tested over a range of *Reynolds Numbers* by varying propeller rotational and advance speeds. The result of the experiments is used to identify the minimum *Reynolds Number* at which the performance characteristics of the model propeller i.e. thrust coefficient, torque coefficient, etc. become stable. Flow visualizations on propeller models have confirmed that on model propellers with diameters between 168 mm and 355 mm, the boundary layer flow is mainly laminar on both the suction and pressure sides of the propeller blade at the propeller *Reynolds Number*, R_n below $1x10^6$ (Jessup *et al.* 2002). Between $R_n = 1x10^6$ and $1x10^7$, the boundary layer develops into fully developed turbulent flow, first on the suction side and then on the pressure side. For full-scale propellers, the flow is usually fully turbulent. The exact or critical R_n at which the flow becomes fully turbulent is dependent on factors such as the geometry, load conditions and flow conditions [1]. For the present study, two separate *Reynolds Number* effect experiments were carried out, namely: the 'propeller only case' and the 'pod unit case'.

A podded propulsion system consists of a fixed pitch propeller driven by an electric motor through a short shaft. The shaft and motor are located inside a pod shell. 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 can be directed anywhere in the horizon in a 360° compass. Figure 1 shows the typical arrangement of a podded propulsion system.

Two types of podded propulsion systems are used: puller and pusher. The general arrangement of these two systems is shown in Figure 2, which shows that the pusher and the puller podded propellers have opposite hub taper angle.

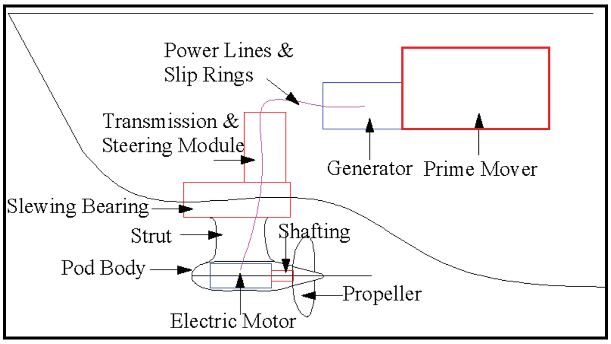


Figure 1: Typical components of a podded propulsion system

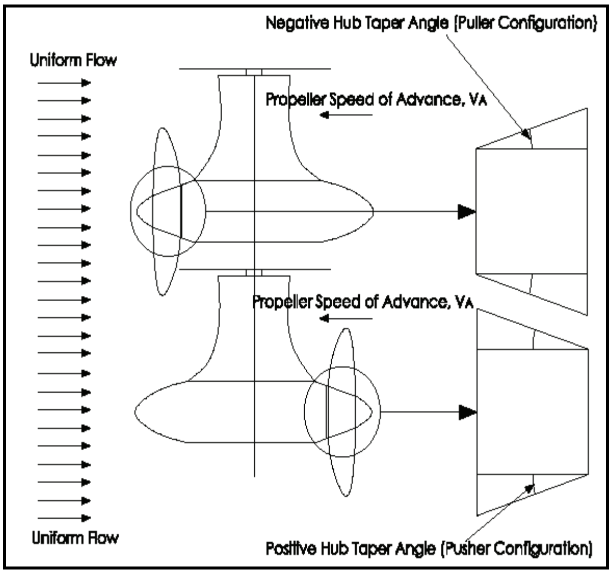


Figure 2: Podded Propulsion Systems; puller and pusher podded propulsion system.

For complex propulsion systems such as podded propulsors, scale effects become more complex due to the number of interactions occurring between individual components of the system, i.e. the strut, pod and propeller. With respect to podded propulsor open water experiments, this flow becomes important both in pusher and puller configurations, but with respect to different components of the systems. As discussed in [2], the scale effect is an important issue for pusher propulsors as well as for a puller propulsor. In a puller system, the propeller operates in a more or less uniform flow with only small effects of the hull boundary layer at the top sector of the propeller plane and with a certain blockage effect of the pod housing behind the propeller. The flow field around pod-strut body is largely influenced by the propeller slipstream velocity and static pressure. Thus, the flow around the pod-strut body becomes almost as turbulent as in full-scale operating condition. Special consideration about the *Reynolds Number* effect on the propeller is required in this case. In the case of pusher propulsors, the top sector of the propeller works in velocity deficit contours off the strut. This means the wake field of the model propeller is considerably different from that of the full-scale. Again, the trailing wake shed by the propeller blades does not interact with pod-strut body, although the upstream-induced flow field and low pressure area interacts with the upstream housing to a small extent. Thus, the inflow to the propeller in pusher unit is more turbulent than that of the puller unit. The inflow to the pod-strut body is mainly uniform and laminar.

For free running traditional propellers, the scale effect is generally considered using well established methodology such as ITTC 1978. However, the scale effect on the performance of podded propulsors is still an ambiguous problem. Attempts have been made to solve this issue of extrapolation using a number of empirical methods, the differences between which are as much as the pod manufacturer types involved. Unfortunately, there is no published full scale or varied scale pod performance data available in the public domain to demonstrate the scale effect on the model scale measurements. A number of RANS based investigations on scale effects have been done in [3], [4] and [5]. It has been found that flow detachment on the pod and strut surfaces is delayed at full-scale as compared to the model scale estimates [3]. The strut acts like a lifting device for which reduction of trailing edge separation from model- to full-scale means a strong increase of its lifting capability and consequently, noticeable reductions in pressure drag. Other parts are non-lifting bodies that behave also very differently at model- and full-scale depending on their capability to reduce areas of flow separation as the *Reynolds Number* increases, [4]. This difference in flow conditions is expected to affect the forces and moments generated by the pod unit, both in open water and in cavitation conditions. It is imperative that more measurements are carried out on the propulsive performance of podded propulsor at larger or full scale to shed some light into this scaling issue.

This paper presents towing tank and cavitation tunnel experiment results of two geometrically similar pod units of different sizes. The primary goal of this research work is to demonstrate the scaling effect on the performance characteristics of the propulsors in open water and in cavitating conditions. Two cases of experimental configurations were used, namely: propeller only case and the pod unit case. The propeller only case is associated with the study of propeller only whereas the pod unit case involved study of the propeller attached to the pod-strut body. In the propeller only case, two propellers with the same geometry but different diameter were tested at identical loading conditions and in four quadrants of operation. Also, the two propellers were tested in different cavitating conditions. In the pod unit case, two geometrically similar pod units were tested using two separate custom-made pod dynamometer systems in two towing tank facilities. Multiple static azimuthing configurations were examined for both units.

The details of the model propellers and pod units are given in section 2.1. Section 2.2 describes the experimental set-up and experiment conditions. In section 3, all the experimental results and relevant discussions for the performance of the podded propulsors are provided. A brief discussion on the uncertainty assessments for each of the measurements is provided in section 4. Finally, in section 5 some concluding remarks are presented based on the experimental results and analyses.

2. EXPERIMENTAL SET-UP

2.1 PROPELLER AND POD MODELS

The research included experiments using two model propellers, having the same blade and hub geometry but different sizes, which can be attached to two appropriately sized pod-strut bodies. The diameters of the propellers were 270 mm and 200 mm, both right-handed. The basic geometric particulars of the propellers are given in Table 1, which also presents a photo of the model propellers. More details of the propeller geometry can be found in [6].

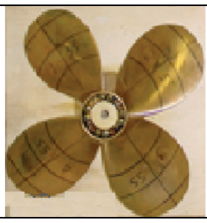
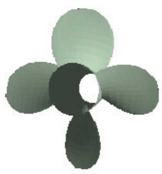
Propeller Parameters	Larger Propeller	Smaller Propeller
Physical/Rendered Model		
Diameter	270 mm	200 mm
Number of blade	4	4
Rotation direction	Right-handed	Left-handed
Design advance coeff., *J*	0.8	0.8
Hub-Diameter ratio, (*H/D*)	0.26 (based on regular straight hub)	0.26 (based on regular straight hub)
Shaft angular speed, n (rps)	15	15
Section thickness form	NACA 66 (DTMB Modified)	NACA 66 (DTMB Modified)
Section meanline	NACA = 0.8	NACA = 0.8
Blade planform shape	Blade planform shape was based on David Taylor Model Basin model P4119	
Expanded area ratio, *EAR*	0.60	0.60
Pitch distribution	Constant, *P/D*=1.0	Constant, *P/D*=1.0
Skew distribution	Zero	Zero
Rake distribution	Zero	Zero

Table1: Basic geometric particulars of the model propellers.

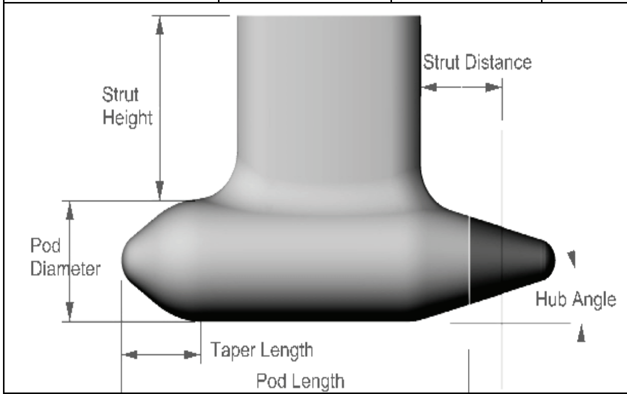
Dimensions of Model Pods	Larger Pod Unit (mm)	Smaller Pod Unit (mm)	Scale Ratio
			
Propeller Diameter	270.0	200.0	1.35
Pod Diameter	139.0	103.0	1.35
Pod Length	410.0	303.7	1.35
Strut Height	300.0	222.2	1.35
Strut Chord Length	225.0	166.7	1.35
Strut Distance	100.0	74.1	1.35
Strut Width	60.0	44.4	1.35
Fore Taper Length	85.0	63.0	1.35
Fore Taper Angle	15°	15°	-
Aft Taper Length	110.0	81.5	1.35
Aft Taper Angle	25°	25°	-

Table 2: Geometric particulars of the two pod-strut models (the picture shows the Geometric parameters used to define pod-strut geometry).

The geometric particulars of the pod-strut models were defined using the parameters depicted in Table, which also presents the particulars of the two pod-strut bodies. As the propeller size was the factor being considered in the study, only the size was varied in the two pod-strut bodies. The bigger pod with a 15° fore taper angle was used in combination with the bigger propeller with 270 mm diameter, and the smaller pod with a 15° fore taper angle was used in combination with smaller propeller with 200 mm diameter.

2.1 EXPERIMENTAL APPARATUS AND APPROACHES

The experiment facilities and apparatus used in the current experimentation are outlined as follows:

- Propeller Only Case Opens Study: The two propellers were tested using a *Kemph* and *Rammers* dynamometer in the OCRE-NRC towing tank facility in open water conditions. The dynamometer measured propeller thrust (T_{Prop}) and torque (Q) at varying advance speeds, rotation directions and propeller orientations to simulate the four quadrants of operations. The facility carriage is designed with a central experimenting area where an experiment frame, mounted to the carriage frame, allows the experimental setup to move

- transversely across the entire width of the tank. The tank is 200 m long and maximum carriage speed of 10 m/s.
- Propeller Only Case Cavitation Study: The two propellers were tested using the *Kemph* and *Rammers* dynamometer in the OCRE-NRC cavitation tunnel facility in cavitating condition under multiple tunnel pressure conditions. The detailed cavitation tunnel configuration is presented in [7]. The tunnel is a closed water circuit with a 2.2 m ×0.5 m ×0.5 m cross-section with rounded corners (radius of 60 mm). Water speed in the tunnel can be varied from 0.0 m/s to 10.0 m/s and the propeller rotational speed from 0 rps to 30 rps. The experiment section pressure (absolute) ranges from 10 kPa to 200 kPa. All torque and thrust measurements were made using the sealed dynamometer.
- Pod Unit Case Opens Study: The bigger pod unit (propeller with pod-strut body) was tested using a custom made pod dynamometer in the Ocean Engineering Research Centre of Memorial University experimenting facility (www.engr.mun.ca) in open water conditions. The details of the pod experiment gear for the larger pod can be founding in [8]. The smaller pod unit was tested using a custom made pod dynamometer in the OCRE-NRC towing tank facility in open water conditions. The details of the pod experiment gear for the smaller pod can be found in [9]. Both pod units were studied at identical azimuthing and loading conditions.

3. RESULTS AND DISCUSSIONS

The propeller dynamometer system used in the cavitation tunnel and towing tank experiments for the 'propeller only case' measure propeller thrust (T_{Prop}) and torque (Q) at different flow and shaft speeds. Both the small and large dynamometer systems measured propeller and pod forces and moments, namely: propeller thrust at hub end (T_{Prop}), propeller torque (Q), unit thrust force (F_X) and moment (M_X), unit transverse force (F_Y) and moment (M_Y), and unit vertical force (F_Z) and moment (M_Z).

The open water propeller dynamometer was calibrated using the ITTC standard method [10]. The pod dynamometers were calibrated using the method described in [11] and [12]. The definition of the forces, moments and co-ordinates that were used to analyze the data and present the results is shown in Figure 3. For the propeller only case, the coordinate centre coincided with the centre of the dynamometer axes. For the two pod dynamometers, the coordinate centre coincided with the intersection of the horizontal axis through the propeller shaft centre and the vertical axis through the strut shaft centre. The results are presented in the form of traditional non-dimensional coefficients as defined in Table 3.

Performance Characteristics	Data Reduction Equation
K_{TProp}	$T_{Prop} / \rho n^2 D^4$
K_{TUnit}	$T_{Unit} / \rho n^2 D^4$ or $F_X / \rho n^2 D^4$
$10K_Q$	$10Q / \rho n^2 D^5$
J	V_A / nD
η_{Prop}	$J / 2\pi \times \left(K_{TProp} / K_Q\right)$
η_{Unit}	$J / 2\pi \times \left(K_{TUnit} / K_Q\right)$
K_{FZ}	$F_Y / \rho n^2 D^4$
K_{FZ}	$F_Z / \rho n^2 D^4$
K_{MX}	$M_X / \rho n^2 D^5$
K_{MY}	$M_Y / \rho n^2 D^5$
K_{MZ}	$M_Z / \rho n^2 D^5$
R_N	$c_{0.7R}$*SQRT(V_A^2+0.7πnD^2)/ν

Table 3: List of performance coefficients for the podded propulsor unit.

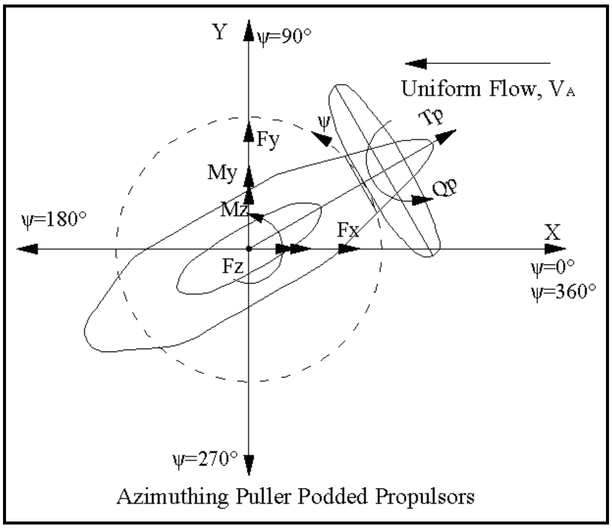


Figure 3: Definitions of forces, moments, and coordinates of a puller azimuth podded propulsor.

3.1 *REYNOLDS* EFFECT EXPERIMENTS-'PROPELLER ONLY CASE'

Table 4 shows the combination of shaft speed and advance speed used to study the *Reynolds Number* effect for the two propellers. For the larger propeller, the shaft speed and the speed of advance must be very high (with rps of 15 and advance speed of 5.06 m/s, the *Reynolds Number* barely reaches the recommended value of 1x10^6). For the smaller propeller, an rps of 30 and advance speed of 4.8 m/s is required to obtain R_n of 1x10^6.

Table 4: Required Reynolds Number on podded propulsors' performance at constant J with varying n and VA (Propeller only case).

Reynolds Number based on propeller chord length, R_n=$c_{0.7R}$*SQRT(V_A^2+0.7πnD^2)/ν, D=200 mm				*Reynolds Number* based on propeller chord length, R_n=$c_{0.7R}$*SQRT(V_A^2+0.7πnD^2)/ν, D=270 mm			
n	V_A	***J***	R_N	***n***	V_A	***J***	R_N
10	0.00	0.00	3.19E+05	10	0.00	0.00	5.81E+05
10	1.60	0.80	3.39E+05	10	2.16	0.80	6.19E+05
10	2.50	1.25	3.67E+05	10	3.38	1.25	6.69E+05
15	0.00	0.00	4.78E+05	15	0.00	0.00	8.72E+05
15	2.40	0.80	5.09E+05	15	3.24	0.80	9.28E+05
15	3.75	1.25	5.50E+05	15	5.06	1.25	1.00E+06
20	0.00	0.00	6.38E+05	20	0.00	0.00	1.16E+06
20	3.20	0.80	6.79E+05	20	4.32	0.80	1.24E+06
20	5.00	1.25	7.34E+05	20	6.75	1.25	1.34E+06
25	0.00	0.00	7.97E+05	25	0.00	0.00	1.45E+06
25	4.00	0.80	8.48E+05	25	5.40	0.80	1.55E+06
25	6.25	1.25	9.17E+05	25	8.44	1.25	1.67E+06
30	0.00	0.00	9.57E+05	30	0.00	0.00	1.74E+06
30	4.80	0.80	1.02E+06	30	6.48	0.80	1.86E+06
30	7.50	1.25	1.10E+06	30	10.13	1.25	2.01E+06
35	0.00	0.00	1.12E+06	35	0.00	0.00	2.03E+06
35	5.60	0.80	1.19E+06	35	7.56	0.80	2.17E+06
35	8.75	1.25	1.28E+06	35	11.81	1.25	2.34E+06
	Min R_n		3.19E+05		Min R_n		5.81E+05
	Max R_n		1.28E+06		Max R_n		2.34E+06

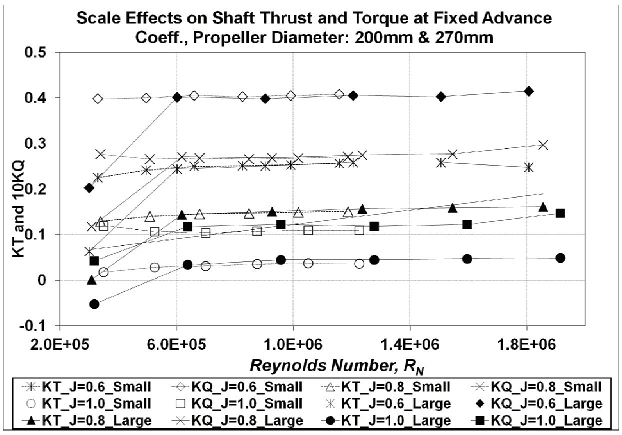


Figure 5: *Reynolds Number* effect on the Open water coefficients of the large and the small podded propellers in 'Propeller Only Case'

Figure 5 shows the *Reynolds Number* effect on the open water propulsive coefficients of the large and the small podded propellers in 'Propeller Only Case'. Figure 6 and Figure 7 show the performance curves of the larger and smaller propellers, respectively, for different *Reynolds Number*. It can be noticed that for the larger propeller, at rotational speeds of 10 or higher, corresponding *Reynolds Number* of 5.81x10^5 or higher, the performance coefficients does not change significantly, which indicate minimum *Reynolds Number* effect. Again, the smaller propeller, at rotational speeds of 15 or higher, corresponding to *Reynolds Number* of 4.78x10^5 or higher, the performance coefficients do not change significantly.

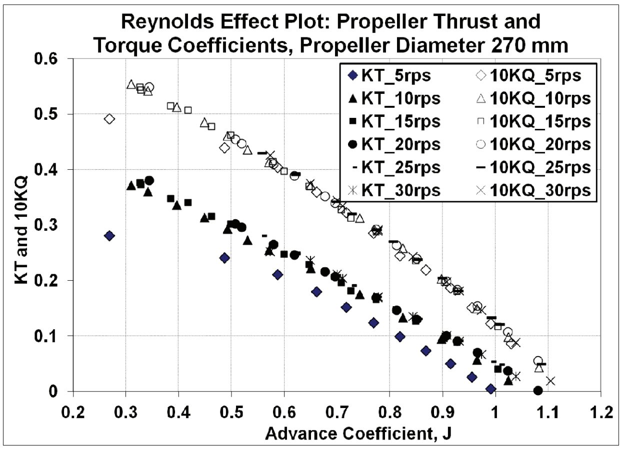


Figure 6: Open water propulsive performance coefficients of the large podded propeller.

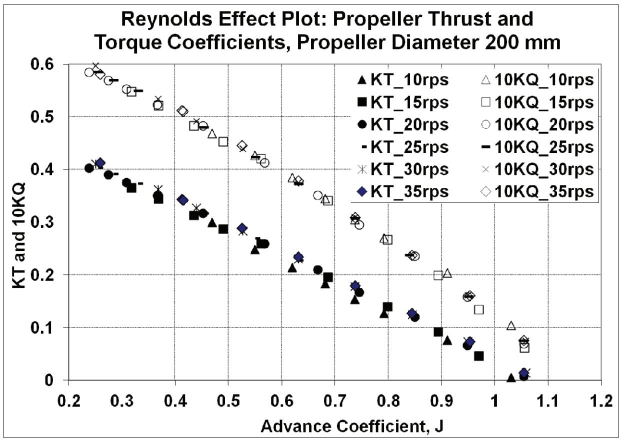


Figure 7: Open water propulsive performance coefficients of the small podded propeller.

It is demonstrated in the results that the propulsive performance of the small propeller stabilizes at lower *Reynolds Number*s than the large propeller; which is in line with previous findings [1]. The K_T and K_Q values were stabilized at values where the turbulent flow has begun to develop. Although the shaft and advance speed used in the current experimentation did not reach the ITTC recommended *Reynolds Number* value of at least 1 million, experiments can still be performed at the different *J* values with the values of *n* and V_A obtained from the *Reynolds Number* study.

The open water propulsive performance coefficients of the large and small propellers are shown in Figure 8 and in Table 5. It is shown that both thrust and torque coefficients of the large propeller are consistently higher than those of the small propeller. Although the differences are within the error limits of the measurements (see section 4), the consistency in the measurement warrants further investigation. The cause of the thrust and torque differences between the same propeller of different sizes could also be partially contributed by model manufacture that causes differences in geometry of the two propellers such as pitch, thickness, and surface finish. These geometric differences could be sufficiently large to cause the same magnitude of the differences measured. Note in Table 5, the percentage differences are calculated using the following formulations:

$$\%K_T = \frac{K_{TLarge} - K_{TSmall}}{K_{TLarge|J=0.0}} \times 100$$

$$\%K_Q = \frac{K_{QLarge} - K_{QSmall}}{K_{QLarge|J=0.0}} \times 100$$

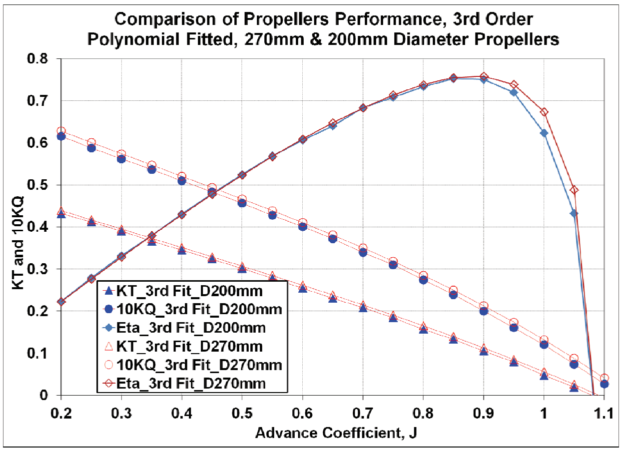


Figure 8: Comparison of open water coefficients of two propellers with varied loading conditions.

J	% Diff K_T	% Diff K_Q
0.2	1.73	2.02
0.3	1.08	1.93
0.4	1.35	1.73
0.5	1.33	1.61
0.6	1.71	1.56
0.7	1.51	1.79
0.8	1.97	1.75
0.9	1.74	1.97
1	2.00	1.88
1.1	1.85	2.20

Table 5: Effect of size on the open water propulsive performance of podded propellers (propeller only case).

3.2 *REYNOLDS* EFFECT EXPERIMENTS- 'POD UNIT CASE'

The pod dynamometer for the larger pod unit was used to investigate the *Reynolds Number* effect of the pod unit. Various combinations of propeller shaft speed and advance speed were used to study the performance of the model pod at various *Reynolds Numbers* in puller configuration. Figure 9 shows the plots of propeller thrust, torque and unit thrust coefficients against *Reynolds Number* at different advance coefficients. It is shown that the value of the performance coefficients start to stabilize at *Reynolds Number* of $6.5\text{x}10^5$, which is equivalent to propeller rotational speed of 11 or more. This is roughly the same for all of the advance coefficient values. This suggests that the pod unit tested at 11 rps or above would have minimum or no *Reynolds Number* effects.

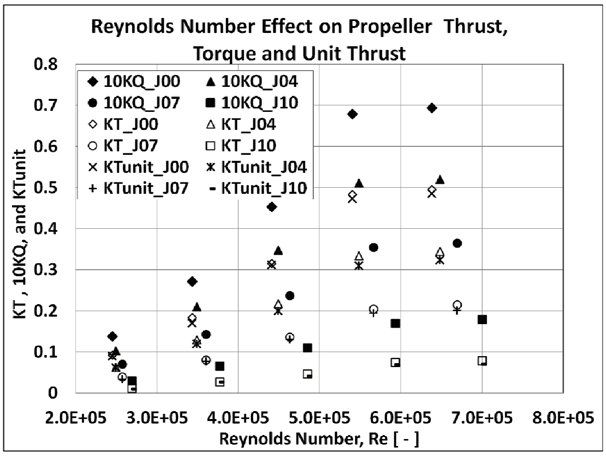


Figure 9: *Reynolds Number* effect experiments on propeller thrust, torque and unit thrust coefficients for the larger podded propulsors.

3.3 FOUR QUADRANT EXPERIMENT RESULTS: 'PROPELLER ONLY CASE'

The propulsive characteristics of the two propellers in the 'propeller only case' in four quadrants of operation are presented in Figure 10. The variations of the performance coefficients with the change of propeller size for varied loading conditions can be found in the same figure. The differences observed in the performance in the quadrants are presented in Table 6. The difference in the performance in the 1st quadrant may be attributed to the differences in the flow conditions around the blade due to size difference, especially the onset of flow separation, which in turn affects the thrust and torque of the propellers. However, the differences in the 2nd and 3rd quadrants may be attributed to the unsteadiness in the flow conditions due to the propeller operating in the off design condition.

Overall, the thrust and torque coefficients for both propellers in the four quadrants show consistent trends. The unsteady nature of the thrust and torque is revealed in the crash-ahead (quadrant 2) and crash-back (quadrant 3) conditions. The percentage differences in the performance coefficient may be due to the differences in size and the uncertainly in the measurements.

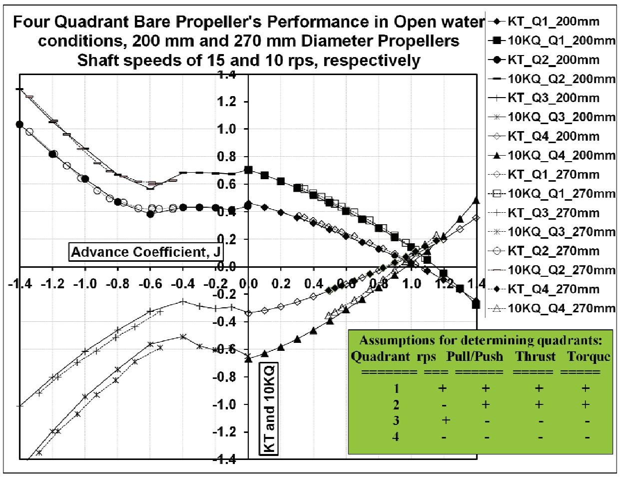


Figure 10: Open water four quadrant experiment results of the 270 mm and 200 mm diameter left handed propellers.

Table 6: Scaling effect on the open water propulsive performance of podded propellers at four quadrants of operation (propeller only case).

	J	K_T	$10K_Q$
Quadrant 1	0.2	2.24%	2.90%
	0.4	2.58%	2.18%
	0.6	2.56%	1.94%
	0.8	2.14%	2.08%
	1	2.32%	1.51%
Quadrant 2	-0.2	3.88%	4.35%
	-0.4	4.57%	1.16%
	-0.6	-5.01%	-7.26%
	-0.8	-3.57%	-4.13%
	-1	3.31%	3.07%
Quadrant 3	-0.2	-7.65%	6.47%
	-0.4	-5.47%	7.70%
	-0.6	-2.05%	-2.15%
	-0.8	1.66%	-2.11%
	-1	4.75%	2.89%
Quadrant 4	0.2	-6.96%	-7.73%
	0.4	-3.17%	-6.00%
	0.6	-1.98%	-7.20%
	0.8	-3.61%	-8.00%
	1	-5.57%	-9.19%

3.4 STATIC AZIMUTHING EXPERIMENTS: 'POD UNIT CASE'

The propulsive characteristic of the two pod units in open water conditions and at various static azimuthing conditions are presented in Figure 11 through Figure 15. The effect of scale (scale factor of 1.54) is not very obvious in these results, especially for propeller thrust and torque. It will be shown in the next section that the percentage differences in the thrust and torque of the two propulsors at all azimuthing conditions are within the uncertainty limits of the respective measurements. However, the variations of the unit force and moment coefficients with the change of propeller size for varied azimuthing conditions are very evident, see Table. This may be attributed to the flow condition that prevails around the pod-strut body. The larger unit may have had reduced amount of trailing edge separation, which consequently increased its lifting capability, thus having higher side force in azimuthing condition.

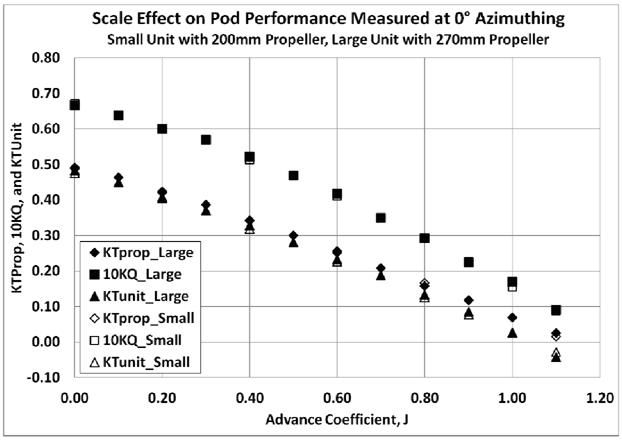


Figure 11: Propulsive Performance of the large and the small podded propulsors at 0° azimuthing condition

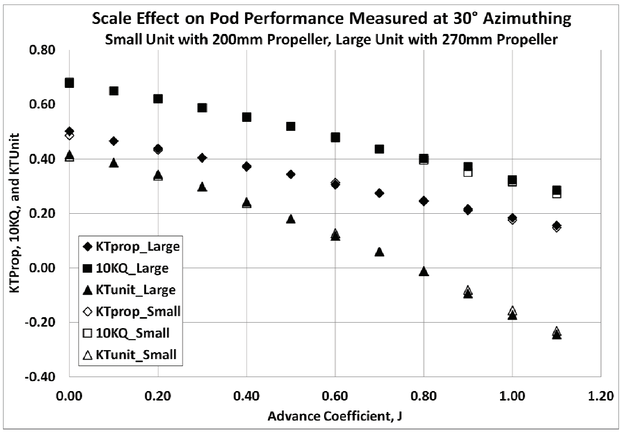


Figure 12: Propulsive Performance of the large and the small podded units at 30° azimuthing condition

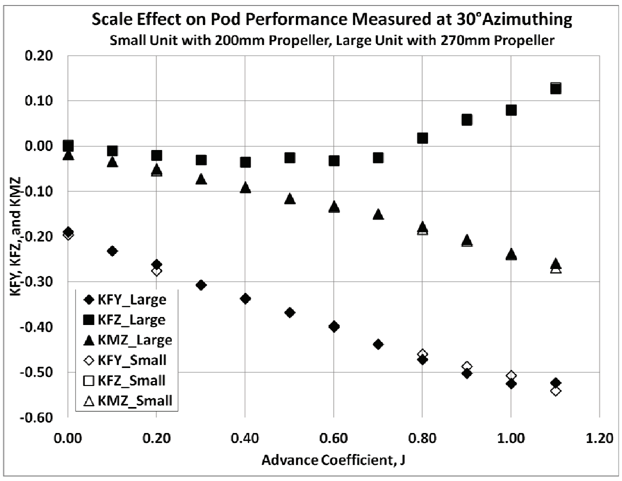


Figure 13: Unit forces and moments of the large and the small podded units at 30° azimuthing condition

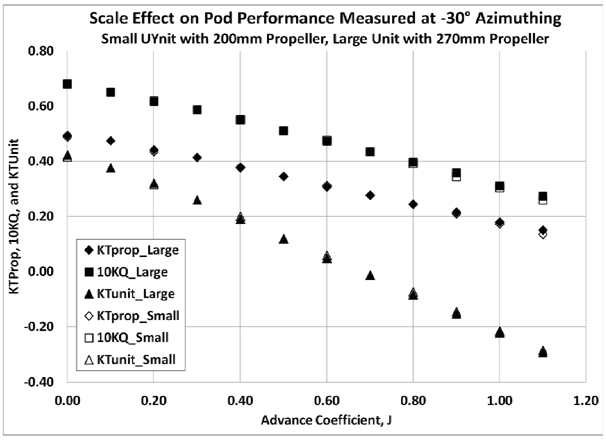


Figure 14: Propulsive performance of the large and the small podded units at -30° azimuthing condition

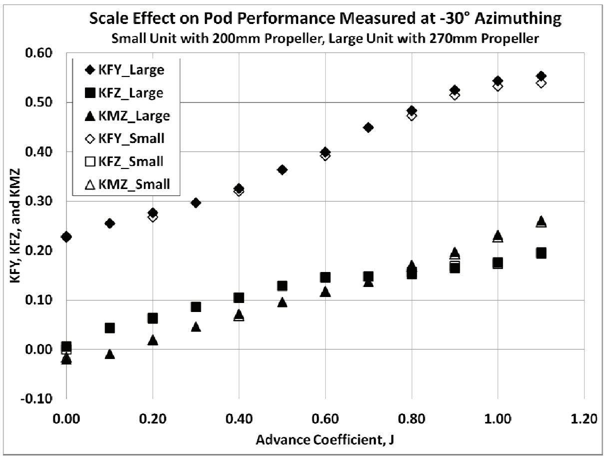


Figure 15: Pod unit forces and moments of the large and the small podded units at -30° azimuthing condition

Table 7: Percentage difference of open water performance coefficients of the large and the small podded units

	J	K_T	$10K_Q$	K_{FX}	K_{FY}	K_{FZ}	K_{MZ}
Straight Ahead	0	0.65	-0.94	1.53	-	-	-
	0.2	1.18	0.42	1.34	-	-	-
	0.4	0.43	1.14	1.48	-	-	-
	0.6	-0.71	0.63	1.55	-	-	-
	0.8	-1.14	0.09	2.29	-	-	-
	0.9	-0.77	0.25	1.24	-	-	-
	1	0.20	1.00	-0.37	-	-	-
	1.1	1.91	1.05	-2.73	-	-	-
+30° Azimuthing	0	2.67	-0.65	2.08	-	-	-
	0.2	0.76	0.16	1.55	-2.91	-0.55	-3.63
	0.4	-0.54	-0.31	1.39	-0.84	1.72	-1.78
	0.6	-1.04	-0.30	-1.50	1.42	3.13	-2.28
	0.8	-0.44	1.15	-1.43	2.67	4.05	-2.29
	0.9	0.42	2.13	-2.46	2.95	4.50	-2.05
	1	1.76	1.43	-2.84	2.75	-0.37	-3.06
	1.1	1.66	1.83	-3.53	-2.97	-2.83	-3.03
-30° Azimuthing	0	1.13	-0.54	1.46	-	-	-
	0.2	1.88	-0.13	1.42	2.47	2.85	-0.60
	0.4	0.44	-0.57	-2.22	2.56	-0.73	0.82
	0.6	-0.63	-0.57	-1.63	2.53	-0.96	1.26
	0.8	-0.08	0.63	-2.67	2.77	-3.21	0.94
	0.9	0.75	1.74	-1.63	1.51	-2.92	2.02
	1	1.82	1.66	-1.44	2.74	1.53	0.26
	1.1	2.85	1.82	-1.91	2.25	0.92	2.04

3.5 CAVITATION EXPERIMENTS: 'PROPELLER ONLY CASE'

One of the main objectives of this experimental study was to investigate the dependency of propulsive performance on the loading conditions at different propeller sizes and at identical cavitating conditions. To this end, comparisons of the performance of the bigger propeller relative to the smaller counterparts are presented for all of the cavitation number experiments.

The two model propellers were tested at different cavitation numbers including the cavitation number at the atmospheric pressure, see Figure 16 and Figure 17. The reference (or nominal) cavitation number, σ_n for a propeller at the shaft centre was defined as follows [13]:

$$\sigma_n = \frac{P_{amb} + \rho g h - P_V}{\frac{1}{2}\rho n^2 D^2}$$

In the above formulation, the nominal cavitation number is based on shaft speed instead of propeller advance speed or propeller resultant speed.

Figure 18 and Figure 19 show the effect of propeller size on thrust coefficient, K_T and torque coefficient, K_Q with increasing cavitation number and at three advance coefficients. It can be seen from the figures that at all cavitation numbers, the large propeller produced more thrust and torque than the small propeller at lower advance coefficients and the difference reduced at increasing advance coefficient (up to J of 0.8). The extents and characteristics of cavitation on the blades of the two propellers are different, which results in different thrust and torque values, especially at low cavitation numbers, see Figure 19. At low cavitation number, the small propeller has larger cavitation area on its blades than the large propeller, resulting in lower thrust. This also aligns with the previous observations of larger propellers generating higher thrust and torque due to prevailing flow conditions.

Figure 16: The small propeller in the Cavitation tunnel experiments

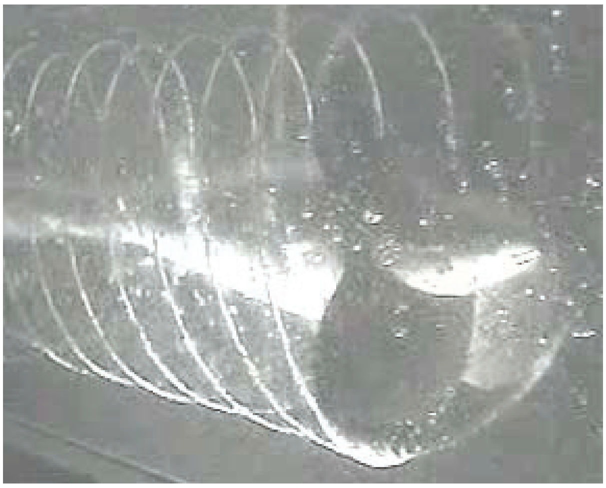


Figure 17: The large propeller in the Cavitation tunnel experiments

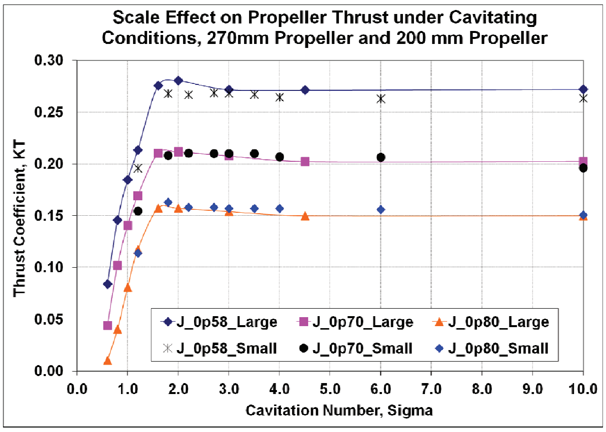


Figure 18: Comparison of thrust coefficients of the two propellers at fixed advance coefficient at different cavitation numbers.

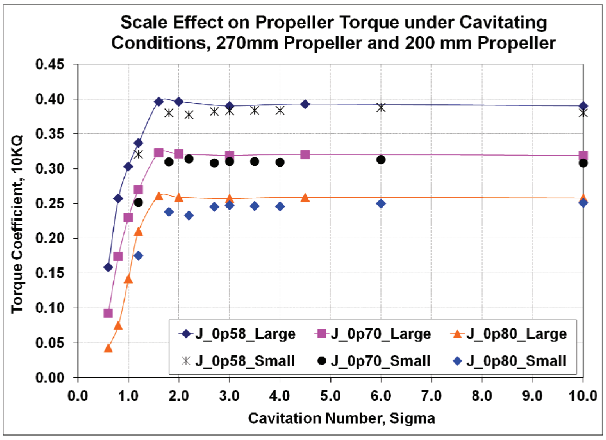


Figure 19: Comparison of torque coefficients of the two propellers at fixed advance coefficient at different cavitation numbers.

4. UNCERTAINTY ASSESSMENTS

Uncertainty analysis was carried out for each of the measurement cases based on the methodology described in [14], [15], and [16]. The error estimates used in the determination of the bias and precision errors in this study are considered to be 95% coverage estimates. The resulting error estimates for the podded propulsor tests in the 'propeller only case', the small 'pod unit case' and the large 'pod unit case' are given in Table 8, Table 9, and Table 10, respectively.

Advance Coefficient, J	**%Error in J, U_J/J**	**% Error in K_T, U_{KT}/K_T**	**& Error in K_Q, U_{KQ}/K_Q**
0.20	4.27	2.18	1.64
0.40	2.24	2.45	1.69
0.60	1.58	2.48	1.84
0.70	1.35	2.56	1.94
0.80	1.23	2.72	2.15
0.90	1.13	2.87	2.27
1.00	1.06	3.06	2.55
1.10	0.99	3.38	3.27

Table 8: Overall uncertainties (in percentage terms) in advance coefficient, propeller thrust and torque coefficients for the podded propellers in 'Propeller Only Case'

Advance Coefficient J	**% Error in J, U_J/J (+/-)**	**% Error in K_{TProp} (+/-)**	**% Error in K_Q (+/-)**	**% Error in K_{FX} (+/-)**	**% Error In K_{FY} (+/-)**	**% Error In K_{MZ} (+/-)**
0.00	-	2.54	1.62	0.90	-	3.90
0.20	1.02	2.90	1.79	0.91	2.81	2.79
0.40	0.59	3.53	2.05	0.94	5.01	2.53
0.60	0.47	3.68	2.51	1.00	3.73	3.80
0.70	0.44	3.61	2.86	1.05	4.00	3.14
0.80	0.42	4.16	3.47	1.16	3.07	4.65
0.90	0.40	4.96	4.42	1.47	5.75	5.30
1.00	0.39	5.93	5.33	3.50	6.82	5.44

Table 9: Overall uncertainties (in percentage terms) in advance coefficient, propeller thrust and torque coefficients and unit thrust coefficient for the small pod unit measurements.

Advance Coefficient, J	**% Error in J, U_J/J (+/-)**	**% Error in K_{TProp} (+/-)**	**% Error in K_Q (+/-)**	**% Error in K_{FX} (+/-)**	**% Error In K_{FY} (+/-)**	**% Error In K_{MZ} (+/-)**
0.00	-	1.19	1.29	1.12	1.97	4.56
0.10	5.20	1.24	1.24	1.15	1.61	2.77
0.20	2.63	1.26	1.31	1.27	1.59	2.08
0.30	1.79	1.31	1.24	1.29	1.34	1.55
0.40	1.38	1.37	1.48	1.51	1.34	1.46
0.50	1.14	1.41	1.31	1.77	1.29	1.23
0.60	0.99	1.51	1.56	2.51	1.26	1.22
0.70	0.88	1.61	1.57	5.07	1.18	1.12
0.80	0.81	1.75	1.42	7.81	1.21	1.09
0.90	0.75	1.89	1.70	3.34	1.14	1.07
1.00	0.71	2.14	2.11	2.94	1.16	1.07

Table 10: Overall uncertainties (in percentage terms) in advance coefficients, propeller thrust and torque coefficients and unit thrust coefficients for the Large pod unit measurements.

The primary element of the uncertainty of the propeller performance coefficients is the bias error (90% or more of the total uncertainty). To reduce the overall uncertainty in the final results, the primary focus should be to reduce the bias error in the equipment. However, for the pod unit case, generally, the primary element of the uncertainty is precision error (about 60% or more of the total uncertainty).

5. CONCLUDING REMARKS

Results of experimental research to evaluate the effect of scale on the propulsive performance of podded propulsors in cavitating and non-cavitating open water conditions and in straight-ahead and azimuthing configurations are presented.

The *Reynolds Number* effect study for the 'propeller only case' showed that the propulsive performance of the small propeller stabilizes at lower *Reynolds Number*s than the large propeller. In the open water condition, both thrust and torque coefficients of the large propeller are consistently higher than those of the small propeller. The differences may be attributed to the uncertainly in the measurements as they are within the error limits. Also, the cause of the thrust and torque differences between the same propeller of different sizes could be partially contributed by model manufacture that causes differences in geometry of the two propellers such as pitch, thickness, and surface finish. These geometric differences could be sufficiently large to cause the same magnitude of the differences measured.

The thrust and torque coefficients for the both propellers in the four quadrants show consistent values with the large propeller having slightly higher thrust and torque in the first and forth quadrants. The unsteady nature of the thrust and torque is revealed in the crash-ahead (quadrant 2) and crash-back (quadrant 3) conditions. The performance differences between the two propellers in open water may be attributed to the differences in the flow conditions around the blade, especially the onset of flow separations which in turn affect the thrust and torque of the propellers.
The propulsive characteristic of the two podded propulsors in open water conditions and at various static azimuthing conditions are presented. The effect of scale is not very obvious for propeller thrust and torque. However, the variations of the unit force and moment coefficients with the change of propeller size for varied azimuthing conditions are very evident, which may be attributed to the flow condition that prevails around the pod-strut body. The larger unit may have reduced amount of trailing edge separation, which consequently increased lifting capability, thus having higher side force in the azimuthing condition.

The two model propellers were tested at different cavitation numbers to facilitate an investigation of the dependency of propulsive performance on the loading conditions at different propeller sizes at identical cavitating conditions. It was found that at all cavitation numbers, the large propeller produced more thrust and torque than the small propeller at lower advance coefficients and the difference reduced at increasing advance coefficient.

The uncertainty assessments confirmed the effect of size in the propulsive characteristics of the podded propulsors both in 'propeller only case' and 'pod unit case'. It was generally found that, the larger propeller generated higher thrust and larger torque than the small propeller at identical loading conditions. The unit forces and moments for the larger pod unit were higher than the small unit. The results presented in this paper shed some light into the understanding of effect of size, hence the extrapolation of podded propulsors' performance characteristics based on model experiments.

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