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Experiments with Podded Propulsors in Static Azimuthing Conditions

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ABSTRACT

The paper presents a comprehensive experimental study of the variations of propulsive characteristics of puller and pusher podded propulsors in static azimuthing open water conditions. A custom designed six-component global dynamometer and a three-component pod dynamometer were used to measure the propulsive performance of a podded unit in pusher and puller configurations in a towing tank. The unit was tested to measure the forces on the whole unit in the three co-ordinate directions as well as thrust and torque of the propeller for a range of advance coefficients combined with the range of static azimuthing angles from +30° to –30° with 5° and 10° increments. The variations in propulsive performance of the unit with change of azimuthing angle and advance speed in the two configurations were examined. The results of the measurements are presented as changes of forces and moments of the propulsor unit with advance coefficients and azimuthing angles. The results illustrate that the axial and side forces and the steering moment are complex functions of the azimuthing angles both for puller and pusher propulsors.

1. INTRODUCTION

Podded propulsors have become a popular main propulsion system. It is accepted that a podded propulsor allows more flexibility in design of the internal arrangement of a ship, potentially reduced noise and vibration, and increased maneuverability, especially in confined space [1].

Szantyr [14, 15] published one of the first sets of systematic experimental data on podded propulsors as the main propulsion unit with static azimuth angles. The tests measured the axial and transverse loads and used traditional non-dimensional coefficients to analyze the data. The study was limited to ±15° azimuth angles. In the work, the effect of an azimuth angle on propeller torque was not studied. Grygorowicz and Szantyr [16] presented open-water measurements of podded propulsors both in puller and pusher configurations in a circulating water channel. Heinke [17] reported systematic model test results with a 4- and 5-bladed propeller fitted to a generic pod housing in pull- and push-mode. In the report, Heinke presented systematic data for forces and moments on the propeller and pod body at different static azimuth angles. Stettler *et al.* [18] also investigated the dynamics of azimuth podded propulsor forces with emphasis on the application of nonlinear vehicle maneuvering dynamics.

In a study of podded propulsor failures, bearing failure was identified as one of the most significant causes of mechanical failure of the propulsors [19]. Detailed study on the bearing forces and moments due to the rotation of the propeller and the azimuthing of pod unit is required to provide sufficient information to the bearing designer.

A research program on podded propellers has been undertaken jointly by the Ocean Engineering Research Centre (OERC) at Memorial University of Newfoundland (MUN), the National Research Council's Institute for Ocean Technology (IOT), Oceanic Consulting Corporation, and Thordon Bearings Inc. The program combines parallel developments in numerical prediction methods and experimental evaluation. Amongst the hydrodynamic issues that have been identified are questions regarding the effects of hub taper angle ([2]-[7]), pod-strut configuration ([2], [7]), pod-strut interactions ([8] and [9]), gap pressure [10], and pod-strut geometry ([11]-[13]) on podded propeller performance. The present study focuses on the variations of propulsive performance of pusher and puller podded propulsors at various static azimuthing conditions under open water operating conditions.

The present study on the azimuth conditions aims to improve the understanding of the behavior of forces and moments that act on the pods. Specifically, the study quantifies the relationship between azimuth conditions and bearing loads (forces and moments on pod bearings). Section 2 details the geometry of the propeller and pod-strut models used in this study and gives a brief description of the apparatus and testing techniques used. Experimental results and discussions are provided in section 3, followed by conclusions in section 4.

2. EXPERIMENTAL SET-UP

2.1 Pod Model

The experiments included tests on two model propellers with a pod unit consisting of a combination of a pod shell and a strut. The propellers had identical blade section geometry but different hub taper angles of 15° and -15° (namely, Push+15° and Pull-15°, respectively). The Pull-15° propeller was a left-handed propeller and the Push+15° propeller was a right-handed propeller. Opposite taper angles were used in the conical hubs of the propellers to fit them with the same pod and strut shell in pusher and puller configurations. The propellers were four bladed with a diameter, D of 0.27m, pitch-diameter ratio (P/D) of 1.0 and expanded area ratio (EAR) of 0.6. The geometric particulars of the propellers are given in [20].

The geometric particulars of the pod-strut model were defined using the parameters depicted in Figure 1. The values for the model propulsor were selected to provide an average representation of in-service, full-scale single screw podded propulsors. The particulars of the pod-strut body tested are shown in Table 1.

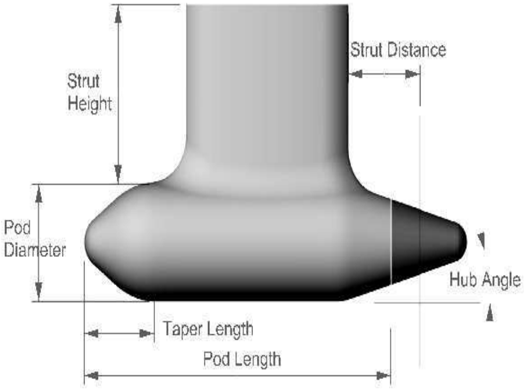


Figure 1. Geometric parameters used to define pod-strut geometry.

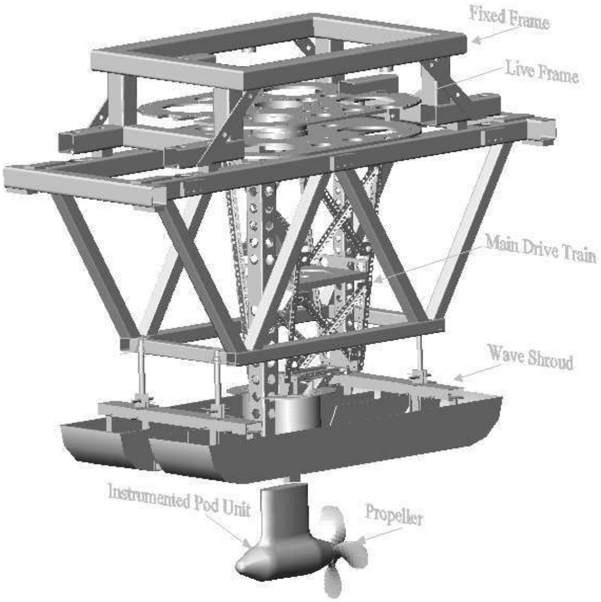
External Dimensions of Model Pods	**Pod 1 mm**
Propeller Diameter, D_{Prop}	**270**
Pod Diameter, D_{Pod}	**139**
Pod Length, L_{Pod}	**410**
Strut Height, S_{Height}	**300**
Strut Chord Length	**225**
Strut Distance, S_{Dist}	**100**
Strut Width	**60**
Fore Taper Length	**85**
Fore Taper Angle	**15°**
Aft Taper Length	**110**
Aft Taper Angle	**25°**

Table 1. Geometric particulars of the pod-strut model.

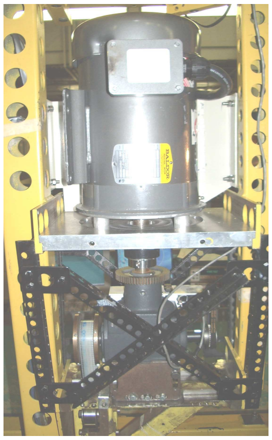
2.2 Experimental Apparatus and Approach

The open water tests of the pod in straight course and azimuth conditions were performed in accordance with the ITTC recommended procedure, Podded Propulsor Tests and Extrapolation, 7.5-02-03-01.3 [21], and the description provided by Mewis [22]. A custom-designed dynamometer system [10] was used to measure propeller thrust, torque, and unit forces and moments. In the instrumentation, a motor fitted above the propeller boat drove the propeller via a belt system.

The center of the propeller shaft was $1.5D_{\text{Prop}}$ below the water surface. A boat shaped body called a wave shroud was attached to the frame of the test equipment and placed just above the water surface. The bottom of the shroud stayed 3 to 5 mm above the water surface to suppress waves caused by the strut piercing the surface. The part of the shaft above the strut (the shaft connected the pod unit to the main drive of the equipment) went through the shroud. Water temperature, carriage speed, V, and the rotational speed of the propeller, n, were also measured. Figure 2 shows the different parts of the experimental apparatus.



(a) the pod dynamometer system [10].



(b) motor that runs the propeller with the gearbox

(c) global dynamometer looking from below.

(d) top view of the arrangement used in the lifting system.

(e) propeller and the pod encasing the pod dynamometer

Figure 2. Different parts of the experimental apparatus used in the podded propulsor tests.

As shown in Figure 2(a), the dynamometer system has two major parts. The first part is the pod dynamometer, which measures the thrust and torque of the propeller at the propeller shaft. The second part of the system is the global dynamometer, which measures the unit forces in three coordinate directions at a location above the wave shroud. Further details of the experimental apparatus are presented by MacNeill *et al.* [10]. The propulsor was placed at different static azimuthing conditions by rotating the entire lower part of the instrumentation (instrumented pod unit and the main drive as shown in Figure 2(a)). The entire lower part hung on a round plate, which had machined marks that defined the azimuth angles.

The pod unit was tested in the puller configuration at different static azimuthing conditions (from 30° on the port side to -30° on the starboard side in increments of 5° and 10°). The propeller, Pull-15 was used in these tests. The entire instrumentation was then set up in reverse conditions to obtain the pusher configuration propulsor by replacing the Pull-15 propeller with the Push+15 one. Similar experiments were carried out in this configuration.

3. RESULTS AND DISCUSSIONS

The pod dynamometer system can measure propeller and pod forces and moments, namely: propeller thrust (T_{Prop}), propeller torque (Q), unit axial/longitudinal force (F_X) and moment (M_X), unit side/transverse force (F_Y) and moment (M_Y), and unit vertical force (F_Z) and moment (M_Z).

For the study of the effects of azimuthing conditions, the measurements were done in puller and pusher configurations using Pod 1 at eleven different azimuth angles. The global dynamometer was calibrated using the method as described by Hess *et al.* [23] and Galway [24]. The methods take into account cross talk between the six load cells and produce an interaction matrix to convert the voltage output into the forces and moments in the three coordinate directions. 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. The coordinate centre coincided with the intersection of the horizontal axis through the propeller shaft centre and the vertical axis through the strut shaft center. In the present paper, only the unit forces and moments are presented in the form of traditional non-dimensional coefficients as defined in Table 2.

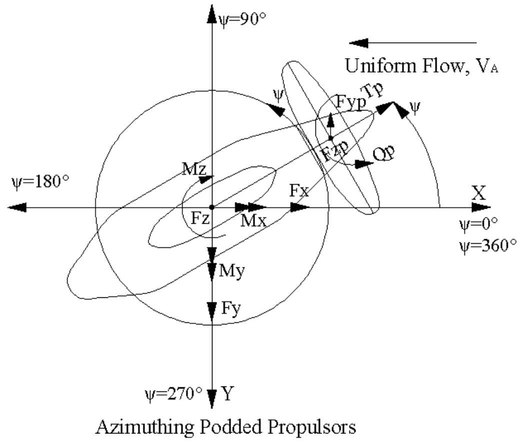


Figure 3. Definitions of forces, moments, co-ordinates of a puller azimuth podded propulsor.

Performance Characteristics	Data Reduction Equation
$K_{T\text{Unit}}$– unit thrust coefficient, $K_{T\text{x}}$ *or Longitudinal force coefficient,* $K_{F\text{X}}$	$T_{\text{Unit}} / \rho n^2 D^4$ or $F_X / \rho n^2 D^4$
$10K_Q$ – propeller torque coefficient	$10Q / \rho n^2 D^5$
J – propeller advance coefficient	V_A / nD
η_{Unit} – unit efficiency	$J / 2\pi \times \left(K_{T\text{Unit}} / K_Q\right)$
K_{FY} – transverse force coefficient	$F_Y / \rho n^2 D^4$
K_{FZ}– vertical force coefficient	$F_Z / \rho n^2 D^4$
K_{MX}– moment coefficient around x axis	$M_X / \rho n^2 D^5$
K_{MY}– moment coefficient around y axis	$M_Y / \rho n^2 D^5$
K_{MZ}– moment coefficient around z axis (steering moment)	$M_Z / \rho n^2 D^5$
T_{Unit} - unit thrust	D – propeller diameter
Q - propeller torque	n – propeller rotational speed
V_A - propeller advance speed, in the direction of carriage motion	$F_{X,Y,Z}$ - components of the hydrodynamic force on the pod

It should be noted that, propeller advance coefficient, J was defined using the propeller advance speed, V_A in the direction of carriage motion (in the direction of X in the inertia frame), not in the direction of the propeller axis.

Table 2. List of performance coefficients for the podded propulsor unit.

The performance coefficients of the propulsor in puller/pusher configuration at different azimuth conditions are influenced by the hub geometry, propeller rotation direction and the interaction with the pod-strut housing. The interaction effect is essentially because of the heterogeneous flow distribution in the propeller plane, induced by the propeller blades, strut and pod housing. The difference in the pod-strut combinations (pusher and puller), means that the flow conditions over the propulsor are very different in the two configurations and this necessitates separate study.

The details of uncertainty analysis of the experimental apparatus are not discussed here. To assess the uncertainty in each set of experiments and to identify the major factors influencing these results, a thorough uncertainty analysis was conducted and presented by Taylor [25] and Islam [26].

3.1 Unit Performance in Puller Configuration

The axial/unit force coefficient, propeller torque coefficient and unit efficiency, side/transverse forces and vertical (steering) moment coefficients of Pod 1 for the range of advance coefficients and azimuth angles tested are presented in Figures 10 to 14. The longitudinal force coefficients, K_{TX} (also called the unit thrust coefficient, $K_{T\text{Unit}}$) decreased as the advance coefficient increased (see Figure 10). As the azimuth angle was increased from 0° to 30° or from 0° to –30°, the unit thrust coefficient, K_{TX} decreased. An exception was found when the azimuth angle was changed from 0° to 10° (Port side) where a small increase in unit thrust coefficient was seen for most of the advance coefficient values (Figure 14a). The reduction of the unit thrust was stronger for the negative azimuth direction, i.e. for the left hand propeller, the clockwise azimuth direction (in the present case, the –10°, –20° and –30° azimuth conditions, see Figure 14a).

Figure 11 shows that the torque coefficient remained approximately the same for 30° (Port) and –30° (Starboard) static azimuth angles. The same conclusion applies for other azimuthing conditions in the two opposite angular positions at all advance coefficient values, with a few exceptions, which might be attributed to experimental uncertainty. Figure 14b shows the variation of propeller torque with the azimuthing angles at different advance coefficients as indicated in the legends (e.g. for the key, J020 means at J=0.20). The propeller torque was not changed much with the change of azimuthing conditions at low advance coefficient values (J<0.40). For higher advance coefficients, the torque coefficient increased with the increase of azimuthing angles (both in positive and negative directions).

The unit efficiency was the lowest at –30° azimuthing conditions and the highest unit efficiency was seen at 5° (port) azimuthing angles for all advance coefficient values (Figure 12). The results also showed that, as the azimuth angles changed from 0° to +30° or from 0° to -30°, the increases/decreases of unit thrust, propeller torque and unit efficiency were nonlinear with the change of azimuth angles.

Figures 13 and 14c show the change of transverse force coefficients with advance coefficient and azimuth angles (at different fixed *J*s). The propulsor showed an increase of transverse force with both positive and negative azimuth angles but in opposite directions with the increase in *J*. Zero transverse force was found in the range of azimuth angles from 2° to 5° (counter-clockwise azimuth) for all of the advance coefficients. The steering moment (vertical moment about *z*-axis) showed a decreasing tendency with the increase of advance coefficients for positive azimuthing angles and an increasing tendency with the increase in advance coefficients for negative azimuthing angles with a steady behavior for straight course conditions.

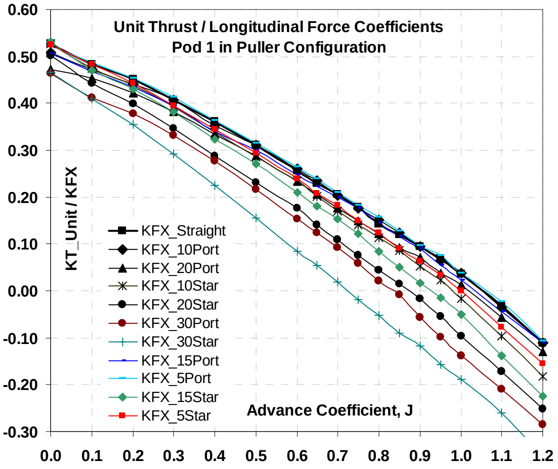


Figure 10. Longitudinal force coefficient plots for Pod 1 at different azimuth conditions.

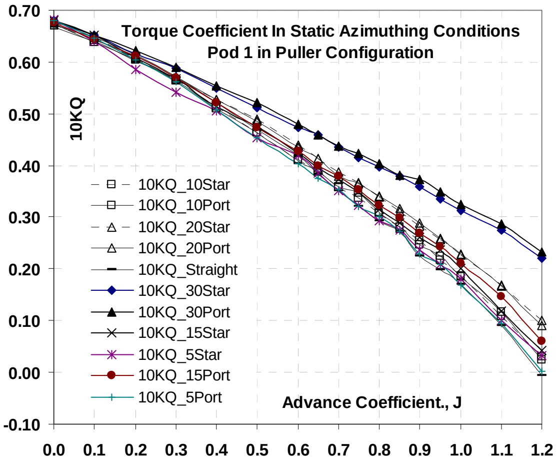


Figure 11. Propeller torque coefficient for Pod 1 unit at different azimuth condition.

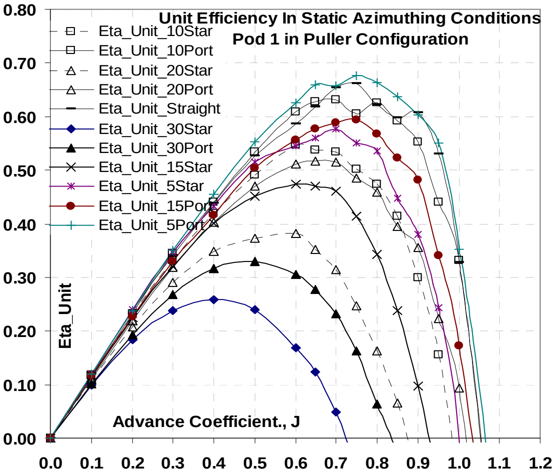


Figure 12. Unit efficiency plots for Pod 1 at different azimuth conditions.

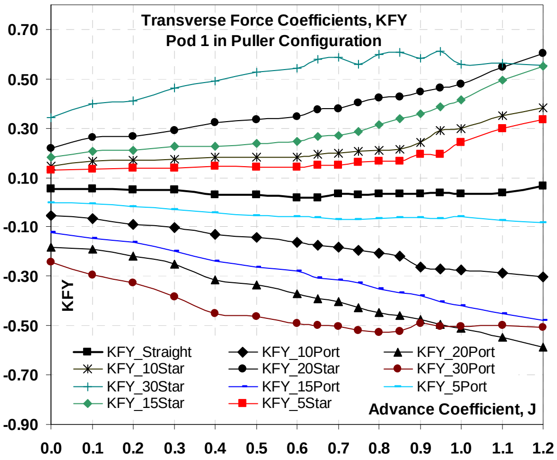


Figure 13. Transverse force coefficient plots for Pod 1 at different azimuth conditions.

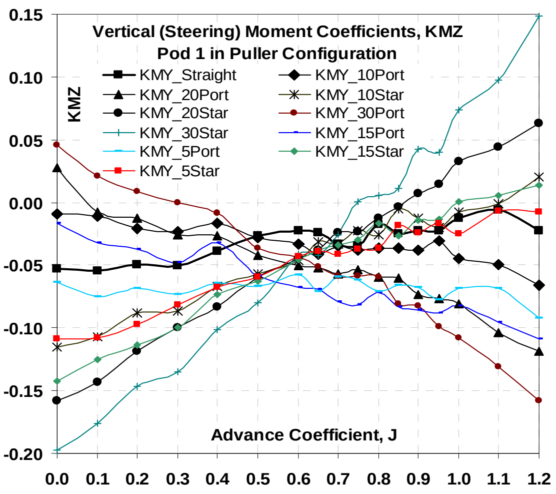
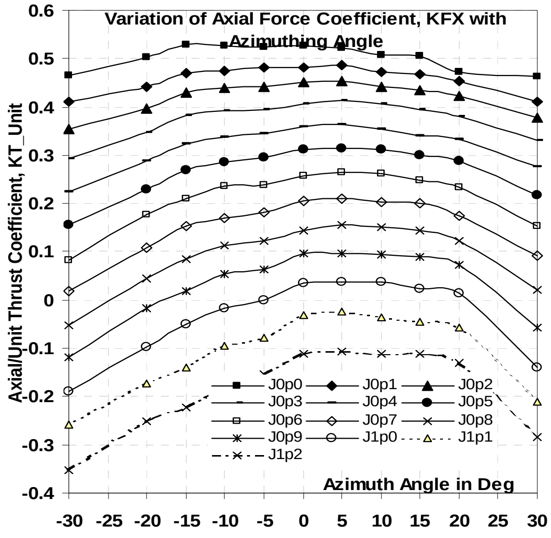
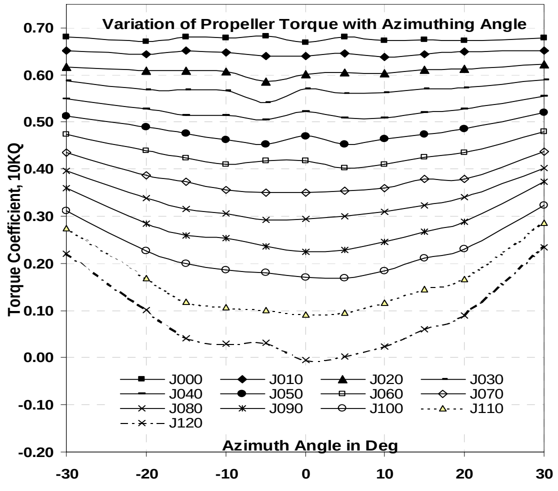


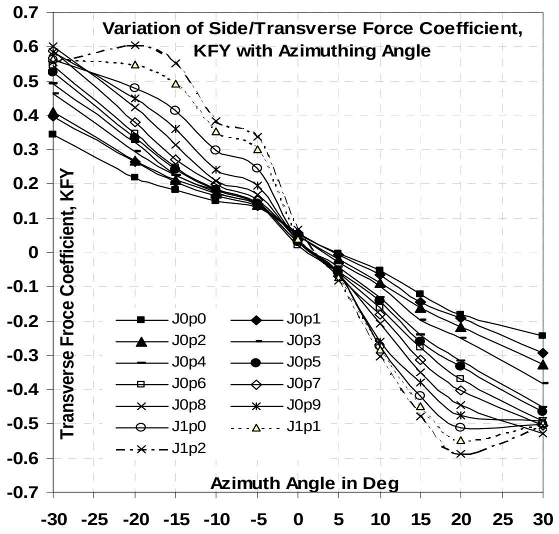
Figure 14. Vertical (steering) moment coefficient plots for Pod 1 at different azimuth conditions.



14(a) Unit Thrust / Longitudinal force coefficient



14(b) Propeller torque coefficients



14(c) Transverse / Side force coefficient

3.2 Unit Performance in Pusher Configuration

After the experiments were conducted in puller configurations, the entire instrumentation was reversed to obtain a set-up in pusher configuration, the Pull-15° propeller being replaced by the Push+15° one. The test results in the configuration are presented in the form of axial/unit force coefficient, propeller torque coefficient and unit efficiency, side/transverse forces and vertical (steering) moment coefficients of Pod 1 for the range of advance coefficients and azimuth angles tested as shown in Figures 15 to 20.

The unit thrust coefficients, K_{TX} behaved somewhat similarly to the corresponding advance coefficients in puller configurations, except the values were smaller in magnitude. The unit thrust decreased for azimuthing from 0 to 30° in both directions as compared to that in straight course conditions. However, a small increase unit thrust coefficient was seen as the propulsor azimuthed from 0 to 15° port side. Similar results were seen for most of the advance coefficient values. The reduction of the longitudinal force was stronger for the negative azimuth direction, i.e. for the right hand propeller, the counter-clockwise azimuth direction (in the present case, the -10°, -20° and -30° azimuth conditions, see Figure 20a).

As shown in Figure 16, for all the advance coefficients, the propeller torque coefficients were higher than those of the straight course conditions for positive azimuth angles and were lower for negative (starboard) azimuth angles. It is shown that for pusher configurations, the maximum torque was found at 30° azimuth angle on the port side and the lowest torque was found at -30° azimuth angle on the starboard side. It was also observed that the propeller torque was less sensitive to the azimuthing angle (in the range of –30° to 30°) on the starboard side than on the port side. In pusher configurations, the highest unit efficiency was seen at straight course operating conditions and the lowest was seen at 30° starboard azimuthing conditions (Figure 17) when the advance coefficient was higher than 0.5.

Figures 18 and 20(c) show the change of transverse force coefficients with advance coefficient and azimuth angles (at different fixed *J*s). The nature and magnitude of the transverse force coefficient with the change of advance coefficient and azimuthing conditions were somewhat similar to those in puller configurations. The zero transverse force was found in the range of azimuth angles from 1° to 3° (clockwise azimuth) for all of the advance coefficients. The steering moment (vertical moment about *z*-axis) showed an increasing tendency with the increase of advance coefficients for positive azimuthing angles and a decreasing tendency with the increase of advance coefficients for negative azimuthing angles with a steady behavior for straight course conditions. The nature of the steering moment coefficient curves was completely different from those in the puller configurations.

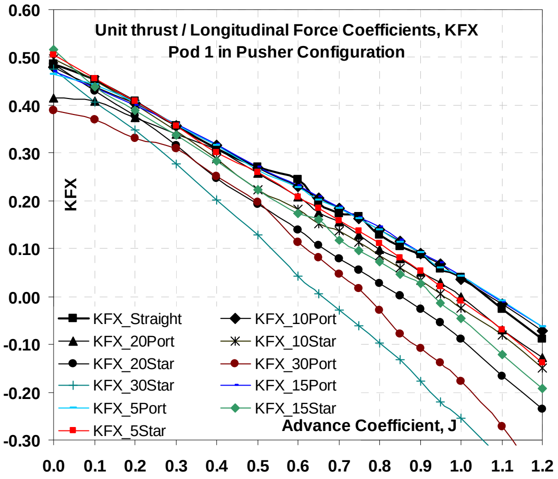


Figure 15. Longitudinal force coefficient plots for Pod 1 at different azimuth conditions.

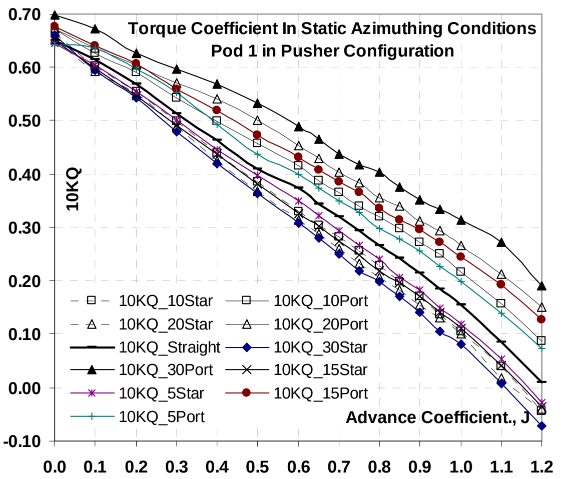


Figure 16. Propeller torque coefficient for Pod 1 unit at different azimuth conditions.

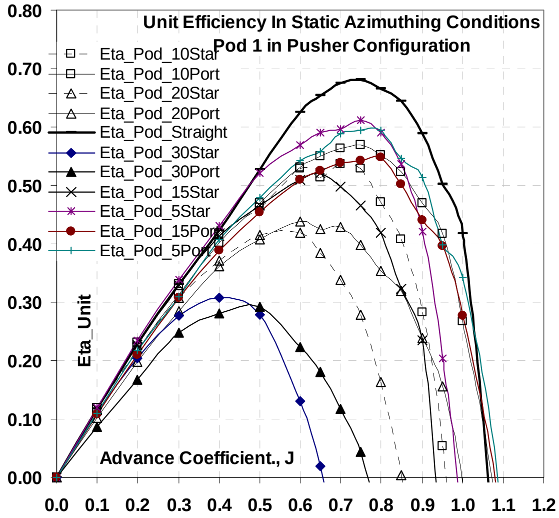


Figure 17. Unit efficiency plots for Pod 1 at different azimuth conditions.

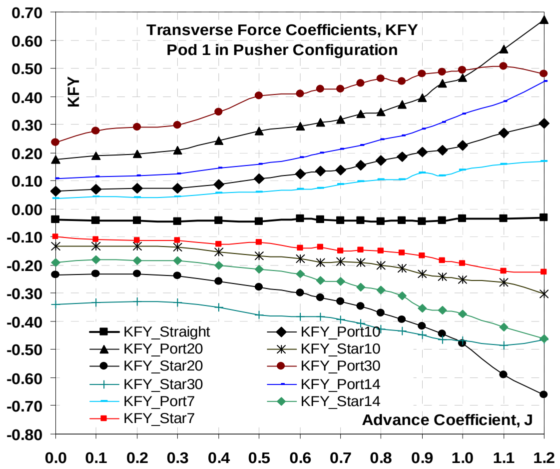


Figure 18. Transverse force coefficient plots for Pod 1 at different azimuth conditions.

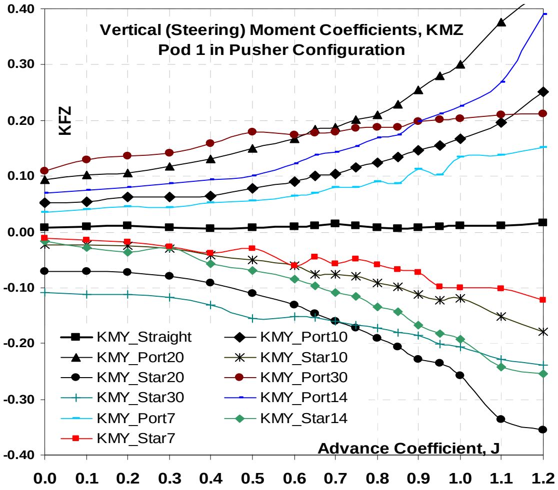


Figure 19. Vertical (steering) moment coefficient plots for Pod 1 at different azimuth conditions

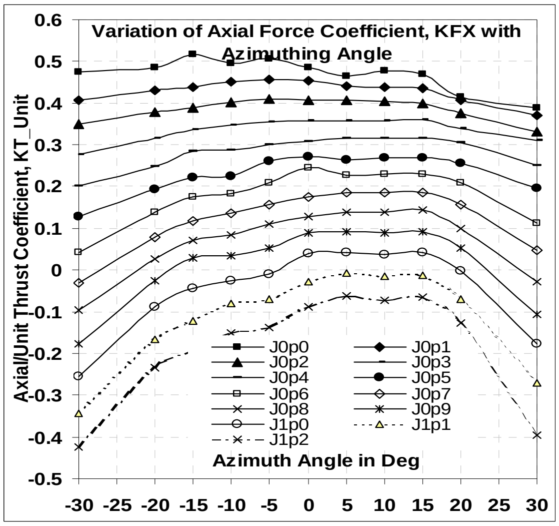


Figure 20(a). Unit thrust / Longitudinal force coefficient

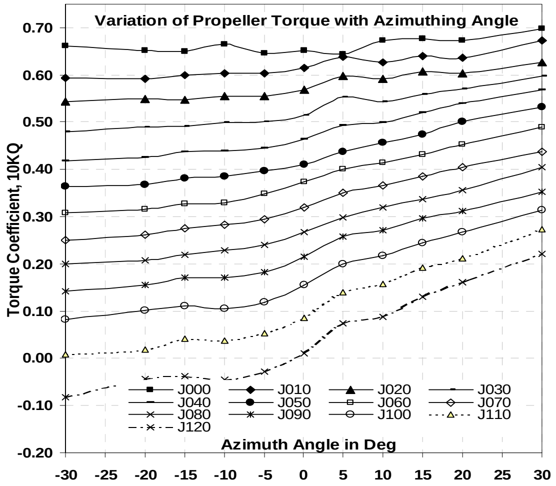


Figure 20(b). Propeller torque coefficient

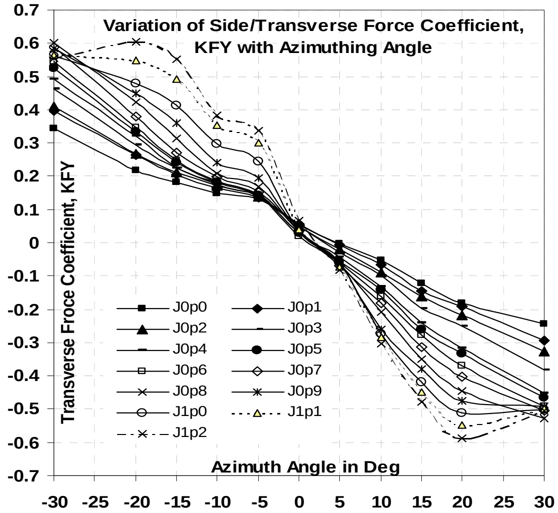


Figure 20(c). Transverse / Side force coefficient

4. CONCLUSION

The present set of experiments investigated the effects of azimuthing conditions on the propulsive performance of podded propulsors in puller and pusher configurations. A model pod fitted with two propellers (for the two configurations) was tested using a custom designed pod testing system.

The unit force and moment coefficients of the propulsors showed a strong dependence on the propeller advance coefficient, azimuth angle and directions. Both in puller and pusher configurations, the unit thrust coefficient decreased with increasing advance coefficient and for both azimuth directions (±30°). In both configurations, the reduction of the unit thrust was stronger for the negative azimuth direction. In puller configurations, the maximum unit efficiency was found at 5° portside azimuthing conditions whereas in pusher configuration, the maximum unit efficiency was found in straight course operating conditions at advance coefficient values greater than 0.5.

Both in puller and pusher configurations, the propulsor with positive azimuth angles showed an increasing transverse force with the increase of *J* and the propulsor with negative azimuth angles showed a decreasing transverse force with the increase of *J*. In puller configuration, the zero transverse force was found in the range of azimuth angle from 2° to 5° on the port side, whereas in pusher configuration, the zero transverse force was found in the range of azimuth angle from 1° to 3° on the port side, for all of the advance coefficients.

In puller configuration, the steering moment (vertical moment about *z*-axis) showed a decreasing tendency with the increase of advance coefficients for positive azimuthing angles and an increasing tendency with the increase of advance coefficients for negative azimuthing angles with a steady behavior for straight course conditions. However, in pusher configuration, the steering moment showed an increasing tendency with the increase of advance coefficients for positive azimuthing angles and a decreasing tendency with the increase of advance coefficients for negative azimuthing angles with a steady behavior for straight course conditions. The nature of the steering moment coefficient curves was completely different than those in the puller configurations.

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