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ABSTRACT

Factorial design is a method of experimental design that can be used to increase the value of multi-factor experiments. The method estimates the effects of the individual factors tested on the overall result to determine which factors most influence the outcome of the experiment. This allows the experimenter to run an additional test series that studies in detail the primary factors while legitimately treating insignificant factors as negligible. Podded propulsors are a relatively recent addition to propulsion options for the shipping industry and are a popular alternative to traditional propulsors with ship designers. The geometry of the pod that encases the motor and shaft of the podded propulsor has been primarily guided by the size of available motors. As motor design becomes more refined and flexible, the relationship of the various parameters (diameter, length, position of strut) with respect to performance becomes a more important design consideration. There are a number of geometric parameters that can be used to optimize the design of the pod and five were chosen for the test series. The results that are presented in this paper are the first set of results obtained from a new pod test apparatus at Memorial University. Numerical results that validate the experimental values are presented. The preliminary results show that some of the design factors are significant at certain J values.

1. INTRODUCTION

Figure 1: Azipod from ABB, (ABB.com) (reprinted with permission)

The geometry of commercial podded propulsors (Figure 1) has been dictated by the size of the electric motors that drive the shaft. As technology progresses, and the development of motors advances it becomes valuable to have a clear understanding of the effect of the outer geometry of the pod on the powering performance of the propulsion unit. Karafiath and Lyons of the US Navy [1] performed resistance tests on a selection of different styles of pods, however to date there have been no published results of the effects on performance of the geometry of a pod under power. A research project at Memorial University (MUN) funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) in collaboration with the Institute for Ocean Technology (National Research Council, Canada), Oceanic Consulting and Thordon Bearings includes experimental research into the geometry of pods and propellers for use on pods, numerical work on the performance of pods, and work on the extrapolation of the powering for ships with pods.

The experimental investigation into the geometry of pods presented here involved open water testing of a series of 16 pods that have geometric parameters varied using factorially designed tests. The series was limited to the analysis of 5 geometric parameters. Five parameters require 2^5 or 32 combinations to complete the test series. A fractional factorial design reduced the number of combinations by a factor of 2 [2].

The numerical investigation used the designs of the same 16 pods and predicted the performance in pulling and pushing modes of testing.

2. METHODOLOGY

Using commercial pods as a guide, geometric parameters were selected that allowed variation in the primary dimensions of the pod. The pod length and diameter, taper length, longitudinal position of strut, and hub angle were chosen as defining dimensions (Figure 2) and these were varied around a mean that was determined from existing pods [3]. Values of the primary dimensions were chosen so there was one set of parameters in the series that are higher than the average commercial dimensions and one set lower. The dimensions were then combined to give a series of 16 pods with the dimensions shown in Table 1.

The details of geometry of the propellers are given in [4].

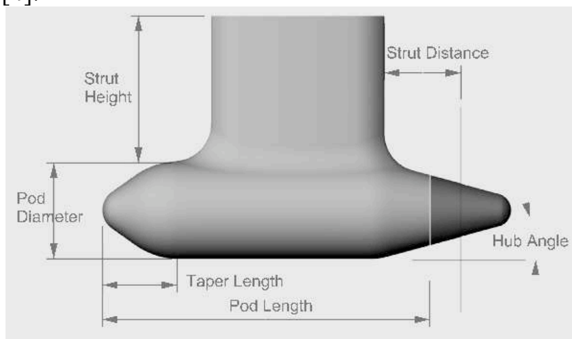


Figure 2 Primary dimensions of pod shell

Table 1: Dimension table of model pods

External Dimensions of Model Pod	**Low Values**	**High Values**
	mm	**mm**
Propeller Diameter	270	270
Pod Diameter	128	166
Pod Length	430	524
Strut Distance	100	133
Taper Length	69	150
Hub Angle (degrees)	15°	20°

The test series is a factorial design, a method of experimentation that can be used to examine the interactions between parameters for multifactor experiments [2]. The method employs estimates of the effects of the individual factors on the overall result to determine which factors most influence the outcome of the experiment. This then allows the experimenter to run an additional test series that studies in detail the significant factors while legitimately treating less significant factors as negligible.

A 2 level factorial design means that in every complete set of runs of the experiment, all combinations of the high and low values of the geometric parameters in Table 1 are studied [2]. Using factorial design, the results of these tests indicate the relative significance of, for example, the change in pod diameter versus the change in strut distance on the performance of the pod unit.

A more complex result might show that changing two geometric parameters together creates a more significant effect on the result than just changing one of the parameters individually. This is a two-factor interaction.

Fractional factorial design is a method that utilizes the experience of the researcher to reduce the number of models required, in this case from 32 to 16, by treating certain combinations as less significant and ignoring 3 and 4 factor interactions. The test series still maintains the integrity of the factorial style design. To reduce the number of combinations a relationship is set up between factors eg: E=ABCD. This relationship is called an alias and the components cannot be differentiated. Therefore a response change due to E could actually be a caused by ABCD but since ABCD is a 4-factor interaction and is being ignored, the response is considered to be that of E. All factors and combinations tested have an alias in a fractional design however the design process ensures that the factors are not correlated [5].

The combinations tested are listed in Table 2 and have been selected to include a combination with all dimensions low and one with all dimensions high. This decision was made to allow further testing comparing two pods directly and comparing these pods with a pod having intermediate dimensions.

A selection of 6 of the 16 pods is shown in Figure 2. Individual pods were constructed for each combination.

Table 2: Combinations of dimensions for 16 pods

Standard Order	**Factors**					
Prop Diameter	**Dprop/Dpod Diameter**	**Dprop/Lpod Length**	**Dprop/SD Strut Distance**	**Dprop/TL Taper Length**	**Hub Angle**	**File/Pod Name**
Constant	**A**	**B**	**C**	**D**	**E**	
1	lo	lo	lo	lo	lo	HiLo_1
2	hi	lo	lo	lo	lo	HiLo_9
3	lo	hi	lo	lo	hi	HiLo_5
4	hi	hi	lo	lo	hi	HiLo_13
5	lo	lo	hi	lo	hi	HiLo_2
6	hi	lo	hi	lo	hi	HiLo_10
7	lo	hi	hi	lo	lo	HiLo_6
8	hi	hi	hi	lo	lo	HiLo_14
9	lo	lo	lo	hi	hi	HiLo_4
10	hi	lo	lo	hi	hi	HiLo_11
11	lo	hi	lo	hi	lo	HiLo_7
12	hi	hi	lo	hi	lo	HiLo_15
13	lo	lo	hi	hi	lo	HiLo_3
14	hi	lo	hi	hi	lo	HiLo_12
15	lo	hi	hi	hi	hi	HiLo_8
16	hi	hi	hi	hi	hi	HiLo_16

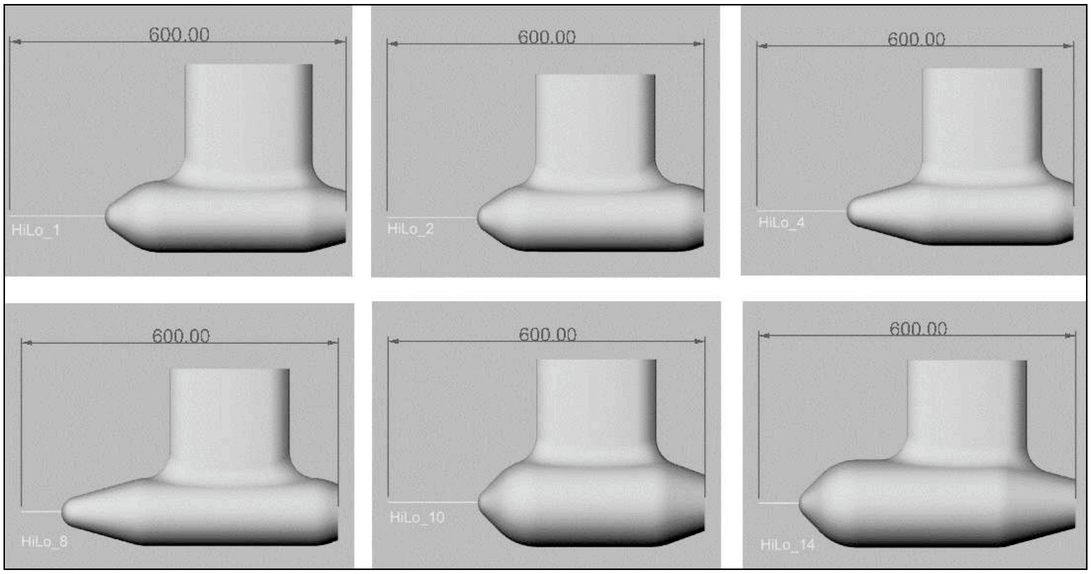


Figure 3: A selection of pods from the geometric series

2.1 EXPERIMENTAL APPROACH

The pods were connected to a dynamometer that was custom designed for this project [6]. Pod # 8 is shown installed in Figure 4. The experimental setup is similar to that recommended by the ITTC 2002 Propulsion Committee, Podded Propulsor Tests and Extrapolation, 7.5-02-03-01.3 [7] and by Mewis of HSVA [8]. The variables measured in each test are those required in the standard open water pod test [7]: velocity of carriage, propeller rpm, propeller torque, thrust of propeller, thrust of unit.

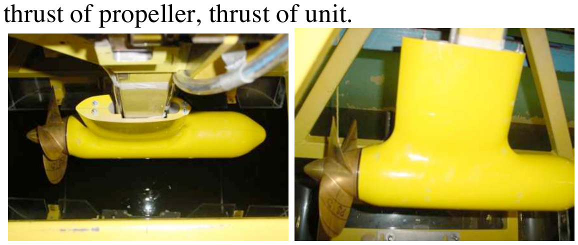


Figure 4: Pod #8 installed on dynamometer

Each test set included standard resistance tests at a selection of velocities, open water pod tests at low thrust values and a number of open water pod tests at varying advance coefficients.

The pod can be run in two modes: pulling or pushing the pod unit. These tests were run in pull mode for the first set of tests, pull mode is also referred to as tractor mode.

2.2 NUMERICAL APPROACH

The numerical study focused on the prediction of the effects of pod-strut geometry on overall propulsive characteristics of pushing and pulling podded propulsion systems in open water conditions.

The low order source-doublet, steady/unsteady time domain panel method code, *PROPELLA*, was modified and used to predict hydrodynamic performance of screw propellers, with and without a pod-strut body attached to it. The structure, functionalities, implementation and demonstration of the code are discussed in detail in Liu, 2003 [9]. A brief description of the numerical model of the multiple-body and multiple-path panel method used in the code is given in Liu, 1996 [10]. In calculating the effect of the pod-strut body on propeller performance, the effect of proximity of the pod-strut body (blockage effect) was considered. In other words, the influence of the panels of the pod-strut bodies on the propeller body was considered in calculating the performance. Interaction effects between the propeller and pod-strut body, the propeller wake and velocity induced by the pod-strut body and the propeller were all taken into consideration. The viscous wake was not modelled. The strut was not considered as a lifting body so the wake of the strut was not modelled. In pusher configuration the propeller operates in the strut wake but this does not necessarily have a significant effect on the overall efficiency of the unit, since the wake extends over a small region of propeller disk. The effect of propeller wake on the strut in puller configuration (wake impingement effect) was not considered. In a recent study [11], it was found that the modified code that includes the wake impingement model does not register an appreciable effect on the prediction of the propeller performance.

The various steps that were followed to include pod-strut geometry into the code are detailed in Islam, 2004 [12]. An illustration of model propeller-pod-strut geometry is provided in Figure 5.

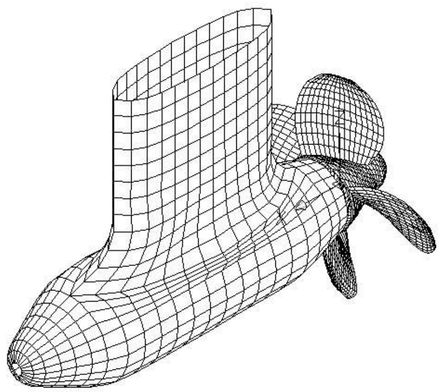


Figure 5: Mesh view of model pod#01 geometry in pull configuration

3. Results

The experimental and numerical results for the pods were analyzed in terms of propeller thrust coefficient, K_T, propeller torque coefficient, $10K_Q$, and propeller advance coefficient, J [7, 13]. K_T, K_Q and J are defined in equations 1-3, respectively.

$$K_T = \frac{T}{\rho n^2 D^4} \quad (1)$$

$$K_Q = \frac{Q}{\rho n^2 D^5} \quad (2)$$

$$J = \frac{V_A}{nD} \quad (3)$$

where, T is the thrust produced by the propeller (N), Q is the torque developed by the propeller (N-m), ρ is the water density (Kg/m^3), n is the propeller rotational speed (rps), D is the propeller diameter (m) and V_A is propeller speed of advance (m/s).

3.1 Experimental Results

The results of the first set of pod experiments are presented in Figures 5 and 6. The experiments were all conducted in the pulling mode at 12 different advance coefficients. A number of pod tests were repeated and showed good repeatability, however it will be valuable to replicate the entire series to validate the presented results.

Figure 5 shows the K_T values for each pod up to an advance coefficient of 1.1. The pitch diameter ratio of the propeller is 1.0 [4]. The K_T values of the different pods range from 0.41-0.51 at J = 0 and 0-0.04 at J = 1.1. Due to the factorial design, these values cannot be compared directly, however the trends show there is some significant variation in thrust with the change of these geometric parameters. There are three distinct groupings of pods; the highest values are for pods 4 and 16, the middle group, pods 1, 2, 6, 12 and 15 and the remaining pods in the lower group. The only common factors in pods 4 and 16 are the taper length and hub angle; they are both set at high values. A high taper length results in a low taper angle so this means that the propeller ends of the pods were less tapered while the aft ends of the pods were more streamlined.

The K_Q results are shown in Figure 7. $10K_Q$ is plotted against J and varies from 0.64 to 0.78 at J = 0 and from 0.073 to 0.19 at J = 1.1. The groupings of pods are less distinct than in the K_T plot. Pod # 3 has the highest values and pods 1, 6, 9, 12 and 15 are the lower value pods.

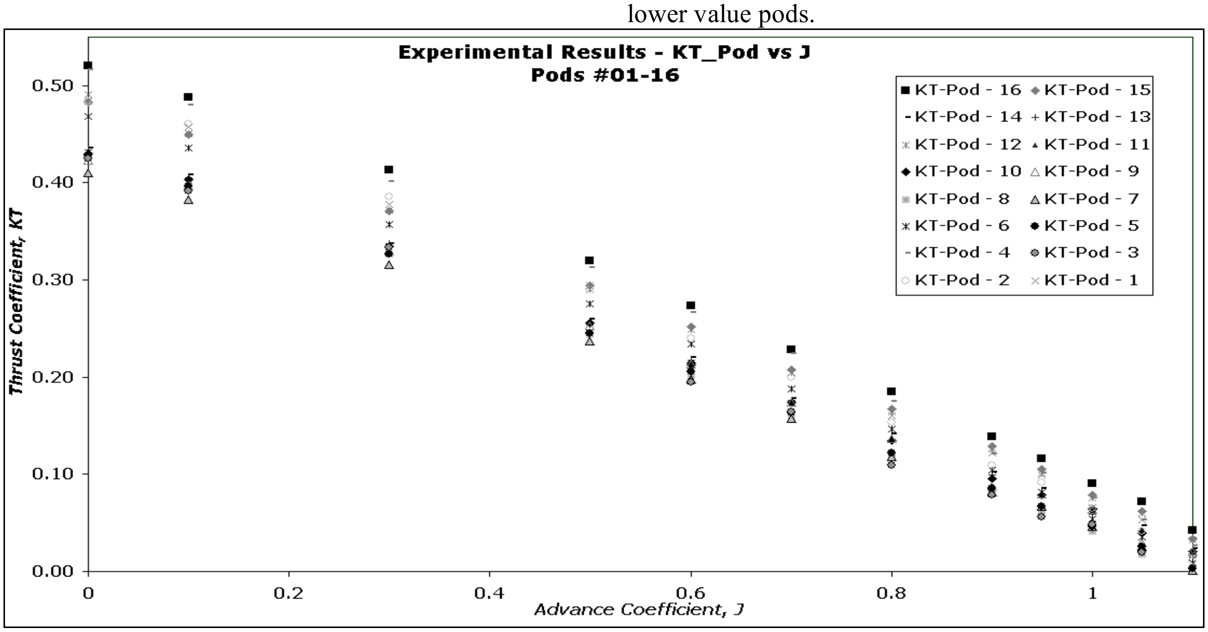


Figure 6: Experimental results - K_T versus J for all 16 pods

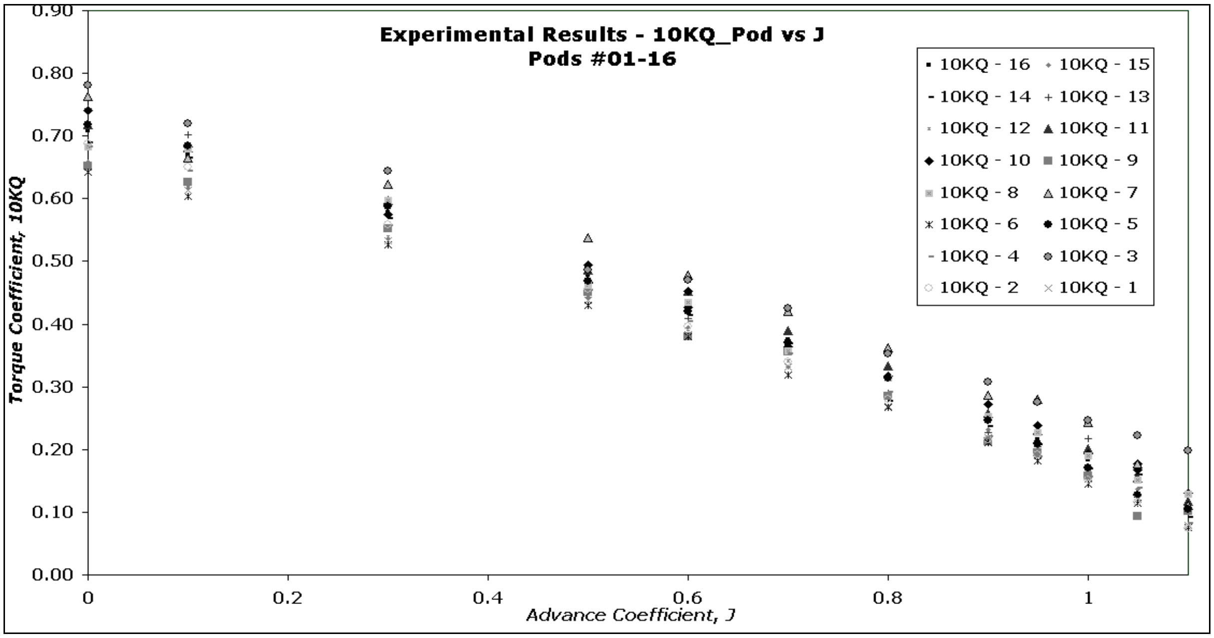


Figure 7: Experimental results - K_Q versus J for all 16 pods

3.2 NUMERICAL RESULTS

The extended code was validated against experimental results of open water tests on four bare propellers in a previous study [4]. In the current study the code was further validated for the propeller with the pod-strut combinations of the 16 pod series. Results from 2 pods are presented in Figure 8.

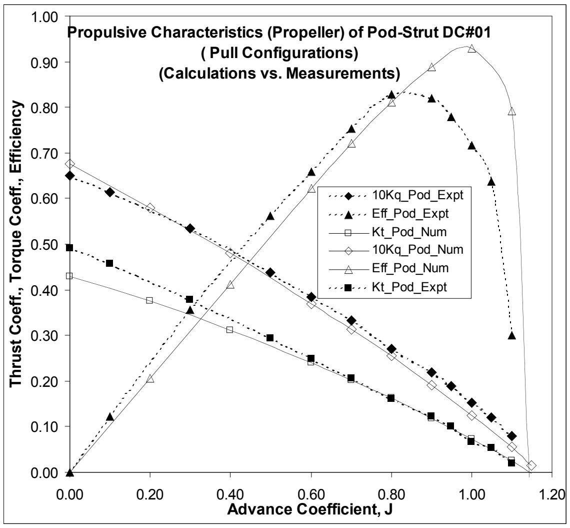
A sample comparison of the experimental and predicted results is shown in Table 3. The positive percentages are numerical values higher than the measurements and the negative percentages are lower than the measurements. All numbers are percentages based on the measured value at J=0.0. The table shows that the predicted value of propeller thrust is lower than the measurements for all J values but the amount is reduced as J increases. The predicted value of propeller torque is slightly higher than the measurement at very low J but slightly lower when J increases. A more advanced formulation to take into account skin friction might improve the predictions at very low J, where blade inflow angle is high.

The K_T and K_Q values for each pod are not presented here because of space restriction. In the predictions, the K_T values of the different pods range from 0.42-0.45 at J = 0 and 0.02-0.06 at J = 1.1. The $10K_Q$ value varies from 0.67 to 0.70 at J = 0 and from 0.044 to 0.099 at J = 1.1. The predicted values of both K_T and K_Q do not spread as much over the ranges of J as shown in the measured values but they show some consistency and similar trends.

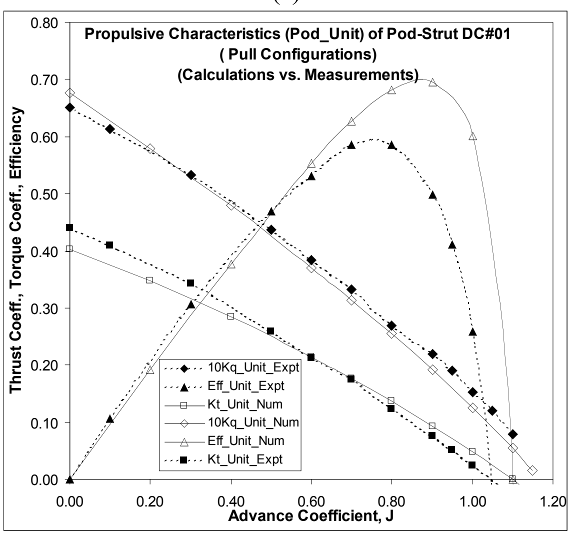
Table 3 Comparison of propulsive performance of the propeller for pod#01

	J	$\%K_T$_Prop	$\%K_Q$
Pod #1	0	-11.06	3.91
	0.6	-4.29	-4.16
	0.8	-3.89	-6.07
	1.1	-5.72	-10.51

The experimental results so far show good comparison with the numerical results, in particular at higher J values; more testing will be completed at low J values. The indications are that further testing, numerical work and comparisons will allow the use of numerical methods to investigate the optimization of pods based on powering performance. One example of the benefits of this approach is that the effects of the strut distance can be evaluated more conveniently and affordably using numerical methods. Different longitudinal positions of the strut can be investigated in a numerical experiment and the extremes can be more easily studied than with physical tests. The experimental apparatus is limited for studying strut distance because of the fixed position of the belt driving the propeller shaft: the belt runs from the dynamometer to the motor on the carriage.



(a)



(b)

Figure 8: Comparison of the measured (Expt) and predicted (Propella) propulsive characteristics of the Pods #01(a) Propeller and (b) Unit

3.3 DOE RESULTS

Data analysis was completed using the experimental design software Design Expert® [13]. The software allows the user to choose a factorial design that meets specific research configuration requirements; in this case the design includes one pod with all-low factors and one pod with all-high factors.

Figure 9 shows the curves for the all-low and all-high pods (pods #1 and #16 respectively). The curves indicate the magnitude of change in K_T over the range of J values for these two pods, using the same propeller.

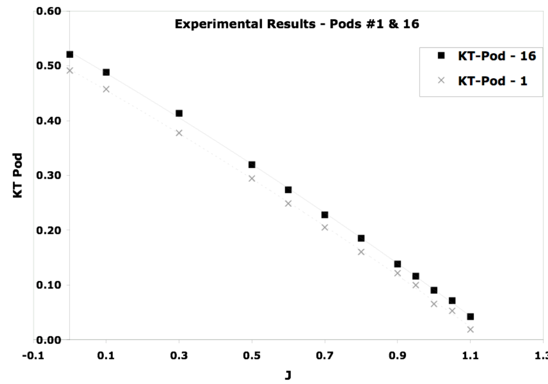


Figure 9: K_T curves for Pods #1 & 16

The Analysis of Variance Approach (ANOVA) [2] was used to examine which geometric parameters of the series have the most significant impact on the performance of the pod. A separate analysis was completed for each advance velocity and the experimental results (Table 4) were compared with the corresponding numerical analyses (Table 5).

The factors were designated as follows:

A Propeller Diameter/Pod Diameter
B Propeller Diameter/Pod Length
C Propeller Diameter/Strut Distance
D Propeller Diameter/Taper Length
E Hub Angle

Table 4: Fractional factorial design results – Experimental

Experimental Work				
J		**Significant terms**		**Noise Error**
0	K_T *Pod*		BD/CE	7.43%
	K_Q		AD, BD/CE	2.11%
0.1	K_T *Pod*	D		0.01%
	K_Q	*none*		57.54%
0.3	K_T *Pod*		BD/CE	
	K_Q			38.60%
0.5	K_T *Pod*		BD/CE	21.00%
	K_Q	*none*		25.03%
0.6	K_T *Pod*		BD/CE	3.34%
	K_Q	B	AB, AD, BD/CE	3.49%
0.7	K_T *Pod*		BD/CE	7.53%
	K_Q	*none*		36.28%
0.8	K_T *Pod*		BD/CE	2.24%
	K_Q	B		8.57%
0.9	K_T *Pod*		BD/CE	10.38%
	K_Q	A,B,	AB, BD/CE	0.30%
0.95	K_T *Pod*		BD/CE	16.54%
	K_Q	A,B	AB,AD, BD/CE	2.30%
1	K_T *Pod*	D	BD/CE	5.67%
	K_Q	A, B	BD/CE	39.20%
1.05	K_T *Pod*	D		1.66%
	K_Q	*none*		13.50%
1.1	K_T *Pod*	D		0.01%
	K_Q	*none*		57.54%

The significant factors that come up repeatedly over the range of J values are A, B, D, AB, AD and BD/CE. The diameter and length are represented by A and B and are expected to have a marked impact on the propeller performance, however they only appear to be significant at mid to high J values and only for the torque. This result may be affected by the quality of the data from some runs as the noise error values for the low J values are quite large and indicate that some additional testing is warranted. However, if this result proves to be reliable then at low J values the effect of diameter and length on the performance of the pod is negligible.

For this test series the factor combination BD is aliased with the factor combination CE because of the choice to keep one all low pod and one all high pod in the series. This means that this highly significant factor is either the combination of the pod length and taper angle (BD) or the combination of the strut distance and hub angle (CE). In addition, the factor D is aliased with BCE. This may not be significant as it is a 3-factor combination and will be ignored at this stage, but it may indicate that the combination of C and E are significant. It is expected that the combination of strut distance and hub angle will significantly affect the performance of the pod unit. It is unlikely that the taper length and pod length combination is more significant than CE because the taper length was not expected to have as great an influence on the performance of the pod as the hub angle in pulling mode.

Table 5: Fractional factorial design results - Numerical

Numerical Work				
J	***K***	**Significant terms**		**Noise Error**
0	K_T	B, C		0.01%
	K_Q	B, C	AB	0.13%
0.2	K_T	C, D	AB, AE	0.01%
	K_Q	C, D		0.23%
0.4	K_T	C, D		0.52%
	K_Q	C, D		1.26%
0.6	K_T	C, D		0.01%
	K_Q	C, D	AE	0.03%
0.7	K_T	A, C, D	AC, AD, AE	0.01%
	K_Q	C, D		0.01%
0.8	K_T	A, C, D	AE	0.01%
	K_Q	A, C, D	AD, AE	0.01%
0.9	K_T	A, C, D	AE	0.01%
	K_Q	A, C, D	AE	0.01%
1	K_T	A	AE	0.01%
	K_Q	A, C, D	AE	0.01%
1.1	K_T	A, C, D	AE	0.01%
	K_Q	A, C, D	AE	0.01%
1.15	K_T	A, C, D	AD, AE	0.01%
	K_Q	A, C, D	AD, AE	0.01%

When the test series was designed it was expected that the hub angle would be significant because it had shown some variation in the results of a previous numerical study [12]. Preliminary analysis of the experimental data indicates that the strut distance and hub angle have a more significant impact on the propeller performance than any other factor or combination of factors over a wide range of advance ratios.

When the numerical results of Table 5 are considered it is clear that both C and D are highly significant over the range of advance coefficients excluding very low advance coefficients. At very low advance coefficients, the factors B and C are significant but as J increases, factors C and D and the interactions AD and AE appear more significant. B, D and AD are also significant in the experimental results and the prevalence of C throughout the numerical data may validate the interpretation of CE as being more significant than BD in the experimental results. The analysis of the numerical version of the factorial design data shows agreement with the experimental results.

4. CONCLUSIONS

The experimental data that has been acquired from the new pod testing system at Memorial University has provided valuable insight into the effect of pod geometry on the powering performance of the propulsion system. Numerical analysis of the same pod series has shown some consistency with the results of testing.

There is a measurable variation in the thrust and torque coefficients over the range of velocities and shaft speeds of the 16 pods tested. While these results must be analysed using factorial analysis because of the experimental design used, Pod#1 and Pod #16 can be compared directly (Figure 9) and used to indicate the effect of changing the overall size and shape of the pod.

The preliminary factorial analysis is showing that while there is overlap between the effect of the combination of strut distance and hub angle, and the combination of length and taper angle, experience combined with previous studies indicate that the strut distance and hub angle combination significantly affect the performance of the pod unit.

The use of numerical methods for pod performance prediction is showing promise, and a valuable next step would be to complete a full factorial analysis where none of the factors are aliased [2] and to compare the results with the ones presented here. If the results show that there is significance in only one of BD or CE and not in the other, then it would be valuable to add a number of physical pods to the existing experimental series to validate this result. Adding new pods to complete a second fractional factorial design would allow the experimenter to ensure that in a new experimental series BD and CE are not aliased together. This could be accomplished with the addition of 4 to 8 pod shells.

The next experimental pod series will include the push mode in the experimental program. It is expected that the length and taper angle combination will have a more significant effect in the push mode than in the pull mode.

5. ACKNOWLEDGMENTS

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