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Study on the Powering Performance Evaluation for the Pod Propulsion Ships

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ABSTRACT

The procedures of model tests and powering performance prediction for twin pod propulsion ships are studied. For model tests, new propeller dynamometer and single component balance for unit thrust measurement were developed and several test set-ups for open water test and self-propulsion test were designed with special effort of propeller dynamometer calibration technique.

The open water tests were carried out at low and high Reynolds number according to the ITTC recommendations with unit total configuration and the interaction effect between propeller and pod housing & strut was studied at different Reynolds numbers. In self-propulsion test, several optimization tests with different direction of rotation, offset distance in beam-wide direction were carried out and each effect on the powering performance were studied.

To the powering performance of pod propulsion ship, the correction methods of pod drag proposed by the ITTC guidelines were investigated with the test data and each effect on the final powering performance was evaluated.

Keywords

Powering performance, pod, open water test, self-propulsion test

1 INTRODUCTION

Nowadays, pod propulsion as a main propulsion system of ship is widespread for various kinds of vessels. The delivery or on-order list of some company shows so many kinds of vessels have adopted the pod propulsion system including cruiser, ferry, icebreaker and tanker since mid of 1990's. (ABB 2008) In general, vessels with pod propulsion system have many benefits over the conventional system like good maneuverability, low noise and vibration level, flexible arrangement of stern part and redundancy design as electric power plant as many people reach a consensus on these. In hydrodynamic design view, a simple hull form of stern part may give some high propulsion efficiency partly due to more uniform inflow to propeller.

In developing specific ship design with pod propulsion system, to find out the powering performance as a combination of hull form and propulsor, a model-scale towing tank test is required. For the conventional propulsion ships, model test procedure, relevant test devices and extrapolation techniques are well-organized, and these have been summarized in ITTC recommendations. (ITTC 2008) Against this situation, propulsion test procedure, test devices and extrapolation methods for pod propulsion ships are still requiring more research efforts, specially focused on developing more reliable test equipment (Gerrit Oosterhuis 2005) and full-scale correction method for pod housing/strut drag.

In this paper, recent research works for developing new test devices including propeller dynamometer/balance and applying these to propulsion test with twin pod configuration are presented. Some details on the calibration technique of dynamometer and balance were discussed. In model test program, special test set-ups for pod unit open water test and self-propulsion test (including optimization for direction of rotation and offset position in beam-wide direction) are described along with ITTC guidance. To get full-scale powering performance prediction, ITTC recommended method is applied to our test data and the results will be discussed.

2 MODEL TEST DEVICES

As mentioned earlier, model test devices including propeller dynamometer and balance for unit thrust for pod propulsion ship have somewhat challenging difficulties. First of all, propeller dynamometer should be immersed into water and this watertightness of dynamometer requires special concern with rotating shaft and sealing problem. Second, the dynamometer is wrapped with specific forms of pod body and shaft, this means it has dimensional restriction, so should be more compact.

In general, there are two approaches dealing with pod propulsion system such as conventional way (regarding pod unit as appendage) and unit base (regarding pod unit as a propulsor). (ITTC 2008) The unit base method is more straightforward and consistent, therefore this is used in our research. In this case, unit thrust measurement should be included and this is more complicated than propeller thrust measurement because this balance for unit thrust measurement should be designed carefully considering motor driving part upward and supporting structure of motor shaft and gearbox downward.

To get more reliable model test device against challenging difficulties mentioned above, the design stages were paid close attention and details are presented in later section.

2.1 Propeller Dynamometer and Its Calibration

2.1.1 Special features of propeller dynamometer

Propeller dynamometer measures thrust and torque by rotating propeller. In pod propulsion configuration, the propeller is placed on the end of pod gondola and details are a little bit different between pulling and puller pod.

Considering acceptable scale ratio, overall dimension of propeller dynamometer was designed by length=250mm, diameter=55mm and model pod housing/strut can be easily wrapped into the dynamometer.

In the design, propeller dynamometer is separated from driving shaft like Figure 1 and this modular design can give us following benefits: dynamometer module is separated from rotating mounting shaft, so some friction by leap seal (to make internal bevel gear watertight) does not affect torque measurement and also helpful to lifetime maintenance of dynamometer due to easy disassembly of that module when there are some problems.

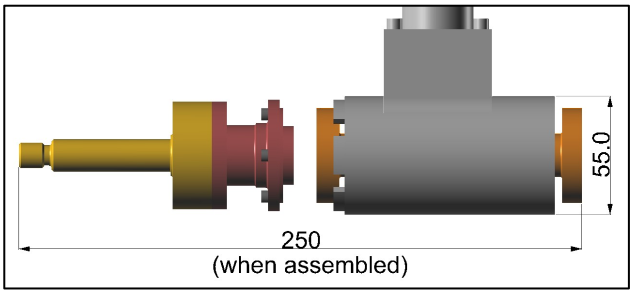

Figure 1 Module design of propeller dynamometer

For this feature of modular design, data transfer and power supply between amplifier and internal full bridge strain gauge circuit is carried out using telemetry technique, so additional electric circuit is build up into the dynamometer and static pick up ring. For reference, specification of propeller dynamometer is as below. (Cussons Technology 2008)

Table 1 Specification of propeller dynamometer

Rated maximum thrust	± 400 N
Rated maximum torque	± 20 Nm
Load sensor	full bridge strain gauge type
Permitted overload	30%
Temperature compensation	feeding with constant voltage

2.1.2 Calibration of propeller dynamometer

After manufacturing the propeller dynamometer, calibration test is carried out to check the performance of dynamometer and to find out the calibration coefficients for tank test. As this dynamometer has the modular design feature and also for high accuracy, the dynamometer is detached from the gearbox and assembled to specially designed calibration stand like Figure 2. This stand has a replica of mounting shaft in gearbox and the propeller dynamometer is fixed on the shaft when calibrated. For thrust, pulling and pushing mode were carried out and clockwise and anticlockwise loading were carried out for torque.

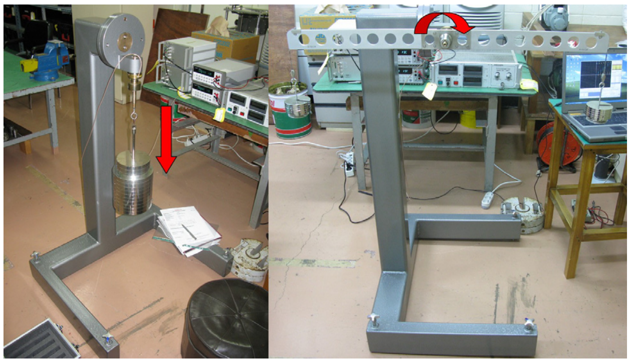

Figure 2 Calibration stand for propeller dynamometer

When calibration test was carried out for thrust, output signal of torque is also measured to check the interference effect from thrust loading to torque sensing part. For torque calibration test, same procedure was applied.

Due to the very small size of the propeller dynamometer, the thrust and torque sensing part are not completely independent in terms of the applied forces and torques. Consequently, thrust has a small influence on the torque output and torque has a small influence on the thrust output like Figure 3. As shown in Figure 3, torque loading has more influence on the thrust output than thrust on torque output.

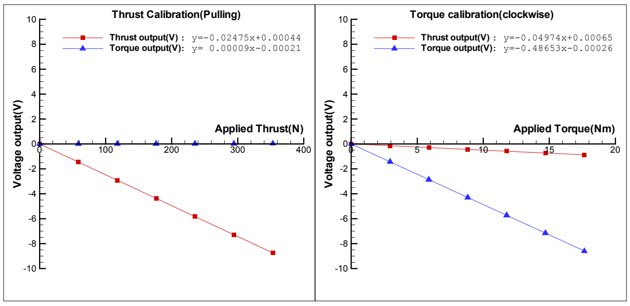

Figure 3 Calibration result and cross coupling effect of propeller dynamometer

As this cross coupling effect when static calibration tests are carried out separately for thrust and torque shows good linearity, the interaction effect can be easily taken into account using 2x2 calibration matrix method for each mode of loading. Details are followed in later section.

This 2x2 calibration matrix method begins with basic linear equation that shows the relation between applied loading and measured signal output of each channel (thrust and torque) when each loading of thrust and torque is applied separately:

$$
\left.\begin{aligned}
MT \ &= a_1 \times AT + b_1 \\
MxQ &= a_2 \times AT + b_2 \\
MQ \ &= a_3 \times AQ + b_3 \\
MxT &= a_4 \times AQ + b_4
\end{aligned}\right\} \qquad (1)
$$

where, Mx = measured output of thrust, MxQ = measured cross output of torque, MQ = measured output of torque, MxT = measured cross output of thrust, AT = applied thrust loading, AQ = applied torque loading. Coefficients $a_{1\text{-}4}$ and $b_{1\text{-}4}$ are the slope (sensitivities) and offset each other.

Against calibration condition, thrust and torque loading are applied simultaneously in real test condition, so above linear equations can be combined as below linear system:

$$
\left.\begin{aligned}
&M = A \cdot L + B \cdot I \\
&\begin{bmatrix} T_{total} \\ Q_{total} \end{bmatrix} = \begin{bmatrix} a_1 & a_4 \\ a_2 & a_3 \end{bmatrix} \cdot \begin{bmatrix} AT \\ AQ \end{bmatrix} + \begin{bmatrix} b_1 & b_4 \\ b_2 & b_3 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \end{bmatrix}
\end{aligned}\right\} \qquad (2)
$$

where, T_{total}=measured output in combined loading condition, Q_{total}=measured output in combined loading condition.

Finally, actual thrust and torque loading can be calculated by two equations and the measured values with the propeller dynamometer:

$$
\left.\begin{aligned}
&L = A^{-1} \cdot M - A^{-1} \cdot B \cdot I \\
&\begin{bmatrix} AT \\ AQ \end{bmatrix} = \begin{bmatrix} a_1 & a_4 \\ a_2 & a_3 \end{bmatrix}^{-1} \cdot \begin{bmatrix} T_{total} \\ Q_{total} \end{bmatrix} - \begin{bmatrix} a_1 & a_4 \\ a_2 & a_3 \end{bmatrix}^{-1} \cdot \begin{bmatrix} b_1 & b_4 \\ b_2 & b_3 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \end{bmatrix} \\
&\rightarrow AT = -40.38839 \times T_{total} + 4.12883 \times Q_{total} + 0.04616 \\
&\quad\ AQ = -0.00772 \times T_{total} - 2.05460 \times Q_{total} - 0.00097
\end{aligned}\right\} \qquad (3)
$$

In equation (3), A matrix and B matrix are results of calibration test presented in Figure 3 for example.

Model test of pod propulsion system has two mode of thrust (pulling and push) and two mode of torque (clockwise and anticlockwise), so totally 4 combinations of linear system can be constituted for each testing mode.

To validate this 2x2 calibration matrix method, combined loading tests were carried out like Figure 4. In these tests, special apparatus was designed to apply thrust and torque loading simultaneously.

From this test set-up and the 2x2 calibration matrix from separate calibration test, the applied loadings of thrust and torque were compared with the calculated loadings.

Table 2 shows the 2x2 calibration matrix method works well and the interaction effect of simultaneous loading of thrust and torque on each output is taken into account successfully.

Table 2 Result of combined loading test

Applied T	Applied Q	Ttoal	Qtotal	Calculated T		Calculated Q	
58.83990	2.94200	-1.60091	-1.42941	58.80254	99.9%	2.94825	100.2%
117.67980	5.88399	-3.20361	-2.85758	117.63633	100.0%	5.89494	100.2%
176.51970	8.82599	-4.80799	-4.28364	176.54669	100.0%	8.83731	100.1%
235.35960	11.76798	-6.40980	-5.70876	235.35713	100.0%	11.77773	100.1%
294.19950	14.70998	-8.00757	-7.12886	294.02513	99.9%	14.70780	100.0%
353.03940	17.65197	-9.60440	-8.54979	352.65173	99.9%	17.63957	99.9%
294.19950	14.70998	-8.00586	-7.12968	293.95268	99.9%	14.70947	100.0%
235.35960	11.76798	-6.40610	-5.70797	235.21095	99.9%	11.77608	100.1%
176.51970	8.82599	-4.80298	-4.28412	176.34236	99.9%	8.83826	100.1%
117.67980	5.88399	-3.19849	-2.85748	117.42996	99.8%	5.89470	100.2%
58.83990	2.94200	-1.59475	-1.43056	58.54900	99.5%	2.95057	100.3%

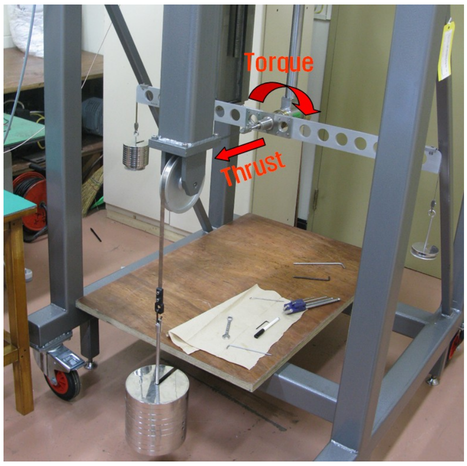

Figure 4 Combined loading test set-up

2.2 Single Component Balance for Unit Thrust

2.2.1 Special features of balance for unit thrust

As mentioned in previous section, there are two approaches to deal with the pod propulsion system assuming it as appendage or total propulsion system and the later method is our selection. In this way, measurement of unit thrust as a whole propulsion system in model testing is required.

In structure design of this balance, it should have function of supporting motor driving system in upper part and driving shaft, gearbox and propeller dynamometer in lower part. This means this balance structure permit the shaft driving as well as force transferring. And also when this balance transfer the unit thrust generated from the pod housing, strut and propeller, it is hardly to know the exact center of this force, so this balance has structural feature that force transferring is to be almost same irrespective of offset position of loading.

Figure 5 Structure of balance for unit thrust measurement

Finally, the balance for unit thrust were designed by two plate structure where upper plate support the motor with encoder and driving shaft, and gearbox and propeller dynamometer are hung on lower plate like Figure 5. For transferring unit thrust when motor shaft is driving, there are two pairs of universal joint between two plates.

2.2.2 Calibration of balance for unit thrust

To calibrate the balance, it is placed on the open water test frame and in this set-up, the upper plate of balance is fixed to the frame and lower plate is free to move in x-direction. By simple lever arm in Figure 5, a unit thrust loading is applied to the balance. Then calibration coefficient can be produced.

As mentioned in previous section, the actual unit thrust loading has offset distance from the lower plate of the balance, an additional calibration test was carried out to check the offset effect on the balance's output as presented in Figure 6.

Figure 6 Calibration of balance with offset position

This test has showed the effect of offset position could be negligible, the difference of output compared to original calibration data by simple lever arm is within 0.1%. If that difference is more considerable, this calibration test set-up should be official test for this balance with presumed offset position.

3 MODEL TEST PROGRAM

Model test program for powering performance of pod propulsion ships is composed of resistance test, pod unit open water test and self-propulsion test. As resistance test with bare hull without pod housing and strut is generic with conventional hull form, this paper skips on this test program without any special concern.

For pod unit open water test and self-propulsion test, pod housing and strut form was designed based on basic dimension from some company's reference with our test vessel's power requirement. (ABB 2008)

3.1 Pod Unit Open Water Test

For the pod unit open water test, special test set-up configuration was designed like Figure 7 with reference to the ITTC recommended procedures and guidelines by ITTC 25th specialist committee of azimuthing pod propulsion.

In this test set-up, the exposed part of shaft between top support plate and the top section of the pod strut is protected by shaft housing, where there should be some gap between shaft housing and shaft because shaft housing itself should not generate any force. This body is well streamlined and fixed to top support plate. Top support plate is just on the free surface, to prevent any free surface effect.

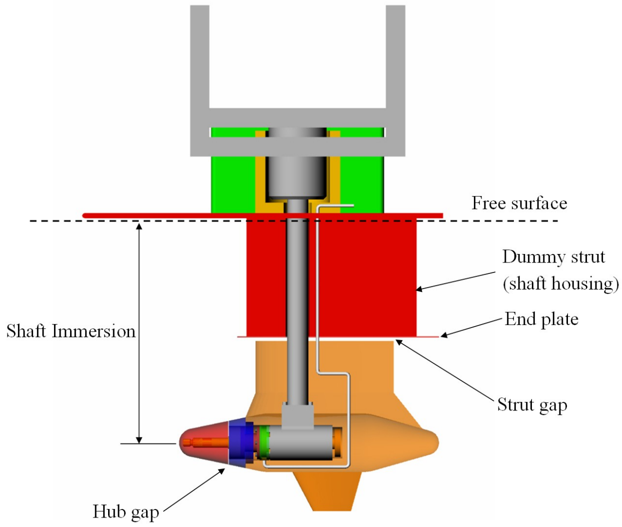

Figure 7 Pod unit open water test set-up configuration

End plate is installed on the shaft housing to prevent any vertical flow induction to the pod strut due to discontinuity between pod strut and shaft housing section.

For the shaft immersion, about 2 times propeller diameter was chosen by ITTC guidance and strut gap were minimized as about 1mm. For the hub gap, about 2mm was chosen and with another gap, unit open water test was carried out to find out the gap effect on the unit open water characteristics.

With this set-up, unit open water tests were carried out for two different Reynolds numbers (low and high), and details of test results are to be followed in later section. For reference, photo for pod unit open water test is presented by Figure 8.

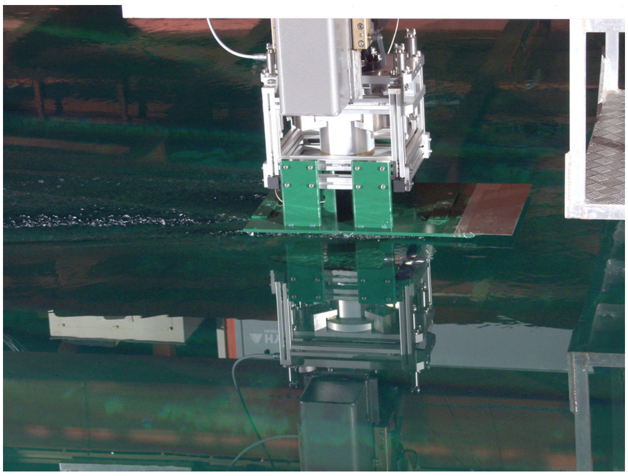

Figure 8 Photo of pod unit open water test

In pod unit open water test, unit thrust and torque of unit pod were measured and the thrust of propeller itself was also measured to calculate resistance of pod housing and strut, where this resistance value will be used as reference for full scale pod drag correction.

3.2 Self-propulsion test

The whole test devices consisting of driving motor, balance for unit thrust and propeller dynamometer wrapped with pod housing/strut is installed on the model ship with twin pod configuration like Figure 9.

In this set-up, direction of rotation of propeller (inward and outward direction) was optimized and also beam-wide direction of twin pod was optimized using sliding mechanism on the guide rails.

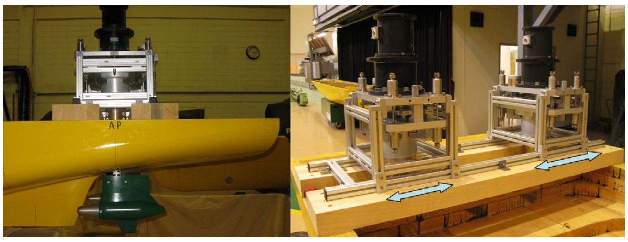

Figure 9 Self-propulsion test set-up with twin configuration

4 TEST RESULTS

4.1 Pod Unit Open Water Test

Principal dimension of propeller used in pod unit open water test is presented at Table 3.

Table 3 Principal dimension of model pod unit

Diameter(m)	0.200	Pod diameter(m)	0.0914
Number of blades	4	Pod length(m)	0.3274
EAR(Ae/Ao)	0.6071	Strut height(m)	0.1366
P/D(mean)	1.0068	Strut chord(m)	0.2143
Tip Skew(deg.)	36.0	Total wetted surface area(m^2)	0.1382
Hub/Dia Ratio	0.285		

In the pod unit open water test, the propeller revolution is fixed and advance speed is varied to change the advance ratio J (=V/(nD)). The characteristic curve of pod unit open water test at low Reynolds (about 3.0×10^5) number is presented as Figure 10.

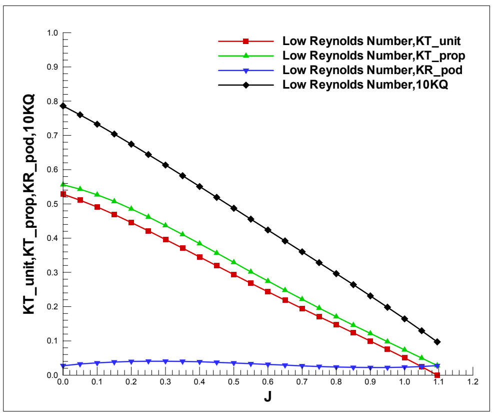

Figure 10 Pod unit open water characteristics curve

Unit thrust of unit pod is measured by single component balance as described in previous section and this force is physically the difference between propeller thrust and pod unit resistance in open water test condition. So the unit thrust curve is lower than the propeller thrust curve in Figure 10.

In figure 10, KR_pod is defined by below equation:

$$KR\_pod = \frac{T_{prop} - T_{unit}}{\rho n^2 D^4} \qquad (4)$$

from measured values of propeller thrust and unit thrust. Like Figure 10, KR_pod is roughly independent of J because pod unit is placed after accelerated flow region by rotating propeller.

The effect of Reynolds number on the characteristics of pod unit open water test is investigated with two different conditions. (low=3.0×10^5, high=5.0×10^5) Figure 11 shows unit thrust, propeller thrust, propeller torque and pod unit resistance at high Reynolds number is lower than the values at low Reynolds number in the whole range of J except some high J region. In average sense, the ratio of values of high Reynolds number with respect to low Reynolds number is unit thrust 99.2%, propeller thrust 97.6%, propeller torque 98.8% and pod unit resistance 82.9% each other. This is mostly due to so called "Reynolds number effect" on the drag of propeller blade and pod housing/strut.

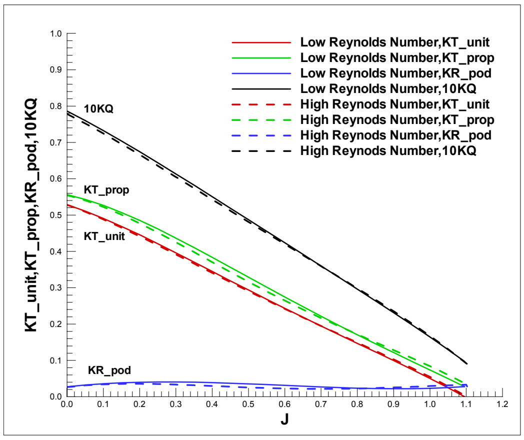

Figure 11 Effect of Reynolds number on POW characteristics

The effect of propeller hub gap in pod unit open water test is known as it is due to the inner pressure existence in the gap. (Rijsbergen and Holtrop 2004) Normally if the gap is more narrower, the pressure effect is more stronger, then the propeller thrust becomes more larger. Actually, in full scale, the gap is around 10mm in order to avoid any problems. But if this gap is applied to model scale, the value is about 0.3~0.5mm and this is not possible to avoid any interference between hub and pod housing. In model test, the effect of gap is investigated with 2.0mm and 3.0mm case and the result is like Figure 12.

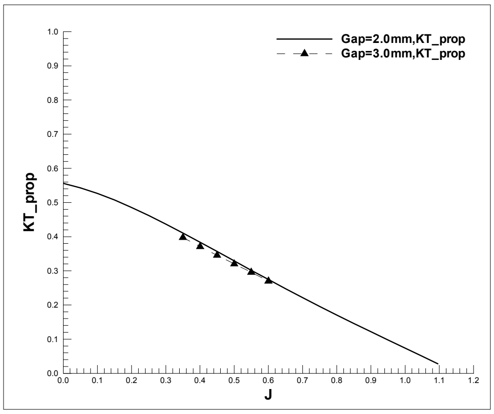

Figure 12 Effect of the gap on the POW characteristics

4.2 Self-propulsion Test

In twin pod configuration of pod propulsion ship, the direction of rotation of propeller and the offset position in beam-wide direction where pod unit is located were optimized for the subject vessel. In optimization test for direction of rotation, the offset position is fixed on 50% of B/2(B is a beam of model ship) and then with decided direction of rotation, optimization test for the offset position is followed.

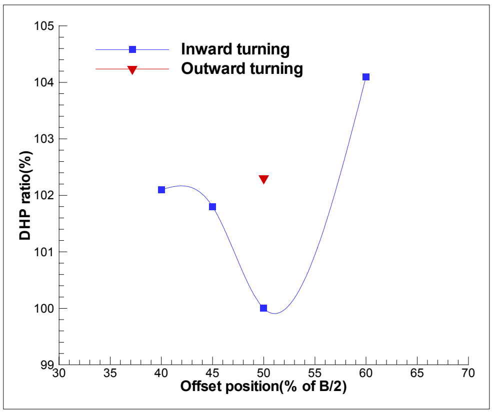

Figure 13 Optimization test of twin pod configuration

Test results and preliminary full scale powering performance prediction are like Table 4 and Figure 13.

Table 4 Propulsion factors in optimization test

Direction	EHP(kW)	wtm	t	wts	EtaH	EtaR	EtaO	EtaD	DHP(kW)
Inward	19017	0.099	0.117	0.099	0.980	0.986	0.656	0.634	29995
Outward		0.104	0.142	0.104	0.957	0.991	0.653	0.620	30673

Y-Direction	EHP(kW)	wtm	t	wts	EtaH	EtaR	EtaO	EtaD	DHP(kW)
40%	19017	0.112	0.150	0.112	0.957	0.996	0.652	0.621	30623
45%		0.108	0.145	0.108	0.958	0.996	0.653	0.623	30525
50%		0.099	0.117	0.099	0.980	0.986	0.656	0.634	29995
60%		0.096	0.155	0.096	0.935	0.997	0.654	0.609	31227

In details of propulsion efficiency in each condition, the dominant factor for difference of overall efficiency is the hull efficiency, η_H that is the interaction effect between hull and pod unit. ($\eta_H = (1-t)/(1-wts)$) When the wake fraction factor is almost same over several conditions, the condition of inward rotation and 50% offset position gives the lowest thrust deduction fraction (t) and this means minimum thrust force is required to overcome the resistance force in self-propulsion condition.

5 FULL SCALE POWERING PERFORMANCE

Full scale powering performance prediction of a vessel with pod propulsion system has basically same procedure as for a vessel with conventional propulsion system. Further consideration is associated with the scale effect of pod unit in open water condition, because the pod unit is regarded as a one propulsor. The scale effect consideration is divided by propeller blade correction and pod housing drag correction. For the blade correction, same procedures can be applied as presented in ITTC recommended procedure and guidelines 7.5-02-03-02.1 "Propeller open water tests" (ITTC 2002).

For the drag correction associated with pod housing, several methods are being used in towing tank facilities worldwide. ITTC 25th specialist committee of azimuthing pod propulsion summarized existing empirical correction methods and proposed simple method to deal with it. (ITTC 2008) In this paper, using this simple method, the test data is analyzed and compared.

5.1 Pod Unit Open Water Performance

The correction method starts with open water test data at high Reynolds number condition. (ITTC 2008) First, propeller blade correction is calculated as ITTC guidance for propeller thrust and torque.

For the drag correction of pod housing, the drag is simply decomposed of 2 components, those are R_{body} and R_{strut}. Then each component can be calculated using empirical formula by principal dimension of pod housing and strut. By these formula, full scale KT_{unit} can be assessed by below equation (5).

$$\left.\begin{aligned}
&(KT_{unit})_{Full\ Scale} = (KT_{unit})_{Model\ Scale} + \Delta KT_{unit} + \Delta KT_{prop} \\
&\Delta KT_{unit} = \Delta R_{POD} / (\rho n^2 D^4) \\
&\Delta R_{POD} = \Delta R_{Body} + \Delta R_{Strut} \\
&\Delta R_{Body} = 1/2 \rho S_{Body} V^2 (1 + k_{Body})(C_{FM} - C_{FS}) \\
&\Delta R_{Strut} = 1/2 \rho S_{Strut} V^2 (1 + k_{Strut})(C_{FM} - C_{FS})
\end{aligned}\right\} (5)$$

where, C_F is model-ship correlation line such as ITTC'57 line, form factor k is calculated by proper empirical formula and V is inflow speed to the pod unit accelerated by propeller rotation.

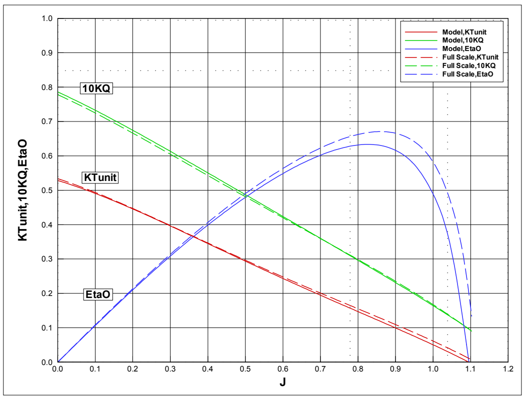

Figure 14 Pod unit open water performance at model and full scale

From equation (5), Δ KT_{unit} can be calculated, then added to the model scale KT_{unit} at high Reynolds number. Finally the open water performance at full scale can be plotted as Figure 14. For the calculated Δ Rpod, comparing with test data of pod unit open water, the scaling factor α (=full scale/model scale in pod resistance) would be about 80% and this means KR_{pod} in full scale is 80% of KR_{pod} in model scale.

The pod resistance components by the empirical formula are compared with model test data. Even though the author cannot find proper empirical formula for R_{lift}, the empirical formula for pod resistance can be considered as reasonable as presented with Figure 15.

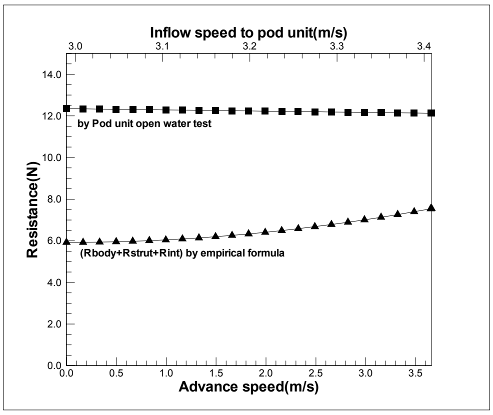

Figure 15 Pod resistance at model scale from model test and empirical formula

5.2 Self-propulsion Performance

Basically, full scale powering performance prediction by self-propulsion factor extrapolation method in pod propulsion ship is identical to the method for a vessel with conventional propulsion system. This means wake fraction factor, thrust deduction fraction and relative rotative efficiency driven by model test can be extrapolated to full scale by ITTC'78 method without any modification.

6 CONCLUSION

For the model test program to find out the full scale powering performance of pod propulsion ship with twin configuration, the test devices including propeller dynamometer and single component balance for unit thrust measurement are designed by new concept to cope with inherent difficulties associated with pod propulsion model test. Correct understanding of test devices' features such as interaction effect of propeller dynamometer between thrust and torque loading would be essential to carry out model test. The interaction effect is clearly figured out with calibration matrix method and single component balance for unit thrust should have proper performance irrespective of offset loading position.

In test program where pod unit is regarded as a whole propulsor, the pod unit open water test has the major impact on the powering performance, so the test set-up configuration should be carefully designed to avoid any source of inaccurate test data like propeller hub gap, strut gap and shaft immersion etc.

From the model test, the Reynolds number effect and propeller gap effect on the pod unit open water characteristics were investigated and these findings will be helpful to improve the test and evaluation procedures of pod propulsion model tests. Self-propulsion tests in several conditions gave the optimum configuration for the direction of rotation and beam-wide position in twin pod propulsion vessel.

In full scale extrapolation procedure, the pod drag correction associated with open water performance was examined along with ITTC recommended simple method by model test data. This showed non-dimensional coefficient of pod drag in full scale is about 80% of the coefficient in model scale and this value can be considered as a clue for the correlation between model and full scale of pod drag.

In near future, further test program including yaw and tilting angle optimization to find out better hydrodynamic efficiency will be arranged, and proper test configuration would be prepared. And also the effort to find out more tuned empirical formula and correlation of pod drag would be continued.

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