

An Estimation Method of Full Scale Performance for Pulling Type Podded Propellers

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ABSTRACT

This study defined the thrust, drag and torque that act on a podded propeller unit, and analyzed the relation among these components. By separating the thrust components of propeller blades and the drag component of pod housing, application of the general concept of thrust correction and drag extrapolation can be made possible. Considering the change in the drag of pod housing resulted from pod propeller operation, estimation method of full scale propulsive performance for the pulling type podded propeller is suggested. In order to estimate the drag of the pod housing, a numerical model of drag velocity ratio, which includes the effects of pod propeller loading and Reynolds number, is presented and evaluated through the comparison of model test and numerical analysis. Especially, the method that can estimate the full scale propulsive performance of a podded propulsor at the stage of power estimation of a ship, which is the early design stage, is proposed.

Keywords

Pod Propeller, Pod Housing, Full Scale, Drag velocity ratio, Drag coefficient ratio

1 INTRODUCTION

Podded propeller is consisted of propeller blades, pod body, strut, and fin, causing hydrodynamic interaction among components, thus makes it difficult to estimate and evaluate the full scale propulsive performance via the methods for ordinary marine propellers. Especially, since the interactions among propeller blades and other components change according to Reynolds number, estimation of full scale propulsive performance from the results of podded propeller model test become more complex and difficult.

Currently, there are various methods for estimating the full scale propulsive performance of a podded propeller (24th ITTC, 2005), however, these are procedures and empirical formula suggested from empirical or semi-empirical approach through estimating full scale propulsive performance derived from the results of model

tests. And the difference of results between each institution's model test and estimation of full scale propulsive performance requires supplementing.

Including the studies announced in the 1st and 2nd T-POD conference, various studies regarding the method and analysis of podded propeller model test and estimation of full scale propulsive performance has been performed, but there is neither standardized process of model testing nor credible full scale propulsive performance estimating method established yet.

Currently, within most of the full scale propulsive performance estimating methods, podded propellers are treated as a propeller unit.

In this study, the basic concept of dividing the podded propeller unit into two parts, propeller blades and pod housing (pod body, strut, and fin) is adopted. Based on this concept, extrapolation method of pod housing drag to full scale was deducted, and applied correction method of propeller blades thrust and torque to full scale. It was aimed to derive a more reasonable and practical full scale propulsive performance estimating method by taking account of the hydrodynamic interaction between rotating propeller blades and pod housing.

A new method for estimating propulsive performance of full scale podded propeller is suggested based on the extrapolation of pod housing drag and the correction of propeller blades thrust and torque.

Also, not only from the propeller open water (POW) test results using ordinary propeller dynamometer, but also suggested full scale propulsive performance estimating process that is applicable in early stage of ship design.

2 ESTIMATION OF POD HOUSING DRAG IN PROPELLER OPERATION

Thrust and torque generated by rotating blades of podded propeller are influenced by pod housing, which is composed usually with strut, pod body and fin. This effect is mainly caused by pressure change due to interference between rotating blades and components of pod housing. Thus the thrust and torque of podded propeller blades in

full scale can be estimated by the use of standard ITTC correction method for conventional marine propellers if included correctly the changes in thrust and torque of the propeller blades due to the interference. While the force acting on the pod housing has different characteristics from the drag in uniform flow due to flow acceleration, pressure change and swirl flow, which are induced by rotating propeller blades. Pressure distribution on each surface of pod body, strut and fin changes differently according to propeller operating condition and the friction changes as well. In fact, because of complexity of the flow, it is very difficult or impractical to estimate or to measure the pod housing drag in propeller operation. In order to solve this difficult problem, a practical method for estimating pod housing drag in full scale is presented, in which an estimation is starting from the drag of pod housing in uniform flow that is relatively easy to measure or simple to estimate, and then updated by including the effects of rotating blades according to propeller loading and Reynolds number on the drag of pod housing in propeller operation.

Thrust, drag and torque coefficients introduced in the present study are defined in appendix.

2.1 Experiment and Calculation for A Podded Propeller

Model tests and flow computations are carried out to construct data base, from which important parameters are found out and relevant equations and logical procedures are derived for estimation of propulsive performance of full-scale podded propellers. The podded propeller of pulling type, which has been studied in previous model tests in the toF tanks of two different model basins, is selected for the present study. The principal dimensions of the podded propeller are given in Table. 1.

Series of model tests are carried out in the large cavitation tunnel (SCAT) of Samsung Ship Model Basin. In order to study the effects of Reynolds number, the flow speed of the test section is varied to 3, 5, 7m/s and at each flow speed, the propeller rpm is changed to cover as wider range of advance ratio as possible within the limitation of the dynamometer for the podded propeller. The dynamometer, made by Cussons of England, was used to measure simultaneously the drag forces of the total unit and the thrusts and torques of the rotating part of the podded propeller. Maximum errors of thrust and torque are 0.14% and 0.10% respectively in the measurement.

Meanwhile, large sets of computations for turbulent flows around the podded propeller in various operating conditions are also carried out by the use of Fluent-Version 2.1 for range of Reynolds numbers from a typical model-scale to full-scale.

The number of grids applied in the numerical analysis was approximately 3.2 million; 2 million in fixed block surrounding ford, strut, and fin, 1.2 million in rotating block around propeller.

Turbulence model used realizable k-e model which is popularly used for numerical analysis of ship, with the standard wall function and the value of y_1^+ used between 100-1200 from scale of a model to an actual ship.

Table 1 Principal Dimensions of the Podded Propeller

Classification	Main Data
Diameter, D_p (mm)	5,600
No. of Blades, Z	4
Expanded Area Ratio, A_E/A_O	0.6068
Mean Pitch Ratio	1.007
Pitch Ratio at $0.7r/R$	1.078
Hub/Dia Ratio. d/D_p	0.285
Tip Skew (deg.)	36.0
Blade Section	NACA 66
Material	Aluminum

2.2 Drag Velocity Ratio

For an estimation of pod housing drag, the drag coefficient of pod housing in uniform flow is first defined as following as the equation (1).

$$C_{D_pod_housing} = R_{pod_housing} / \frac{1}{2} \rho S V_A^2 \quad (1)$$

Here V_A is the inflow speed, S the wetted surface area of the pod housing, ρ the fluid density. Introducing $V_{drag_velocity}$ to include the whole effects of the rotating propeller blades on the pod housing drag, it is possible to express the pod housing drag of the podded propeller in operation as the equation (2).

$$R_{pod_housing_propeller} = \frac{1}{2} \rho S V_{drag_velocity}^2 C_{D_pod_housing} \quad (2)$$

$V_{drag_velocity}$ is a conceptual pseudo-velocity for estimating the pod housing drag to represent the effects of velocity increase with acceleration, pressure changes and swirling wake flow, all of which induced by rotating propeller blades.

From the equations (1) and (2), the drag velocity ratio, γ can be defined as the equation (3).

$$\gamma = \frac{V_{drag_velocity}}{V_A} = \sqrt{\frac{R_{pod_housing_propeller}}{R_{pod_housing}}} \quad (3)$$

In case of operation of podded propeller, equation (3), regarding drag of the pod housing and that alone in open water, is shown in Fig.1 according to each Reynolds number using the results of SCAT's model test and numerical analysis.

Reynolds number is defined with the length of pod in here. ($Rn = V_A L_{pod} / \nu$). As in near the design speed, the result of model test and that of numerical analysis matches very well. Drag velocity ratio increases with the growth of Reynolds number and thrust load. Also, the tendency of the changes holds similarities. This means that when podded propeller operates, the drag of the pod housing changes coherently not only with propeller thrust loads, but also Reynolds numbers as well.

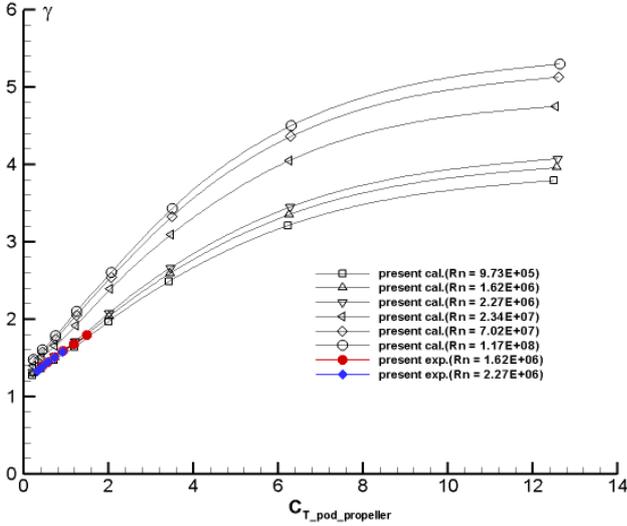


Fig. 1 Variation of drag velocity ratios γ with propeller loads for different Reynolds numbers

With drag velocity ratio given, drag of pod housing during the operation of podded propeller can be easily derived from drag of the pod body in open water, using equation (3). Also, at an initial design stage, after deriving $C_{D_pod_housing}$ through ITTC's empirical formula, it can be applied to equation (3) to estimate the pod housing drag during the podded propeller operation.

A simple method to derive useful drag velocity ratio as above is utilizing Actuator Disk theory. According to this theory, the accelerated velocity due to propeller is the function of propeller thrust load, thus in this study, $V_{drag_velocity}$ is articulated using the drag velocity factor α as below:

$$V_{drag_velocity} = V_A [1 + \alpha (\sqrt{C_{T_pod_propeller} + 1} - 1)] \quad (4)$$

Holtrop and Mennen (2003) performed model tests in order to derive accelerated velocity (V_{inflow}) from identical type of empirical formula and suggested 1.3 as the value of α for pulling type podded propeller.

In this study, α is the drag velocity factor which defines the effect of velocity increase and pressure change due to propeller rotating blades and influence of the swirl flow in their wakes. From the relationship of equation (4), when the change in drag velocity ratio of Fig.1 can be shown as Fig.2 with change in α according to change in thrust loads

of podded propeller and Reynolds number. Change in drag velocity factor α according to thrust loading coefficient is similar to almost all Reynolds numbers, and is showing coherent difference according to Reynolds number.

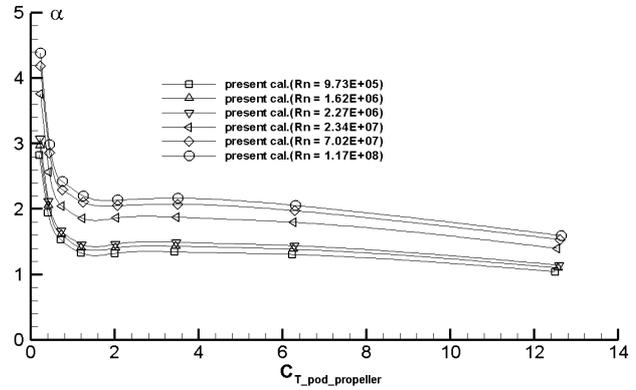


Fig. 2 Variation of drag velocity factors α with propeller loads for different Reynolds numbers

In this study, in order to separately analyze the influences of Reynolds number and thrust loading coefficient, drag velocity factor α is assumed to be multiplication of each following function as below:

$$\alpha = f(Rn) \cdot f(C_T) \quad (5)$$

When the difference of α or ratio according to Reynolds number is consistent throughout the entire thrust load, it is possible to derive the influence to Reynolds number, thus define α_{mean} via average of α regarding thrust loading coefficient for each Reynolds number, and express the change in α_{mean} according Reynolds number as in Fig.3.

The Reynolds number used here is based on a weighted average of lengths of pod, strut, and fin. Thus, since pod housing is consisted of pod body, strut, and fin and the shape is different in each podded propeller, Reynolds number was used for the average length as defined in equation (6).

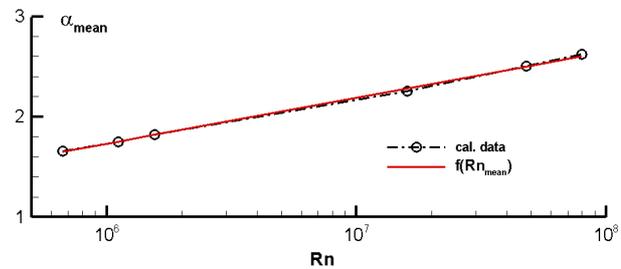


Fig. 3 Change of mean values of drag velocity factors according to Reynolds number

$$L_{mean} = \frac{1}{H} \{ h_{pod} (or D_{pod}) L_{pod} + h_{strut} L_{strut} + h_{fin} L_{fin} \} \quad (6)$$

In this equation, H is the total length from fin bottom to strut top, while h and L are each height and length. As shown in Fig.3, α_{mean} shows a logarithmic growth according to Reynolds number $Rn_{mean}(=V_A L_{mean}/\nu)$, and can be estimated as a function of the Reynolds number as below.

$$\alpha_{mean} = f(Rn_{mean}) \approx 0.460\{\log_{10} Rn_{mean} - 2.235\} \quad (7)$$

If equation (5) is divided by α_{mean} , the function for thrust loading coefficient C_T can be α/α_{mean} , and as in Fig.4, it can be estimated as equation (8).

$$\frac{\alpha}{\alpha_{mean}} = f(C_T) \approx 0.228\{\coth(C_T) + 2.512\} \quad (8)$$

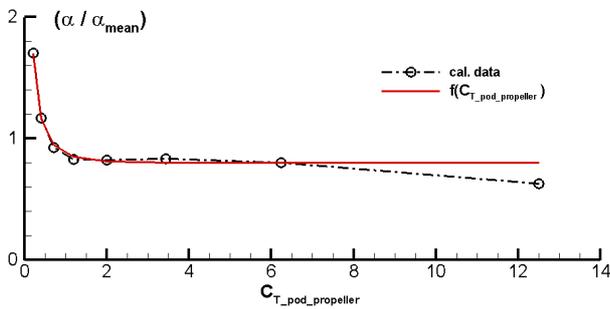


Fig. 4 Change of drag-velocity coefficient ratios according to $C_{T_pod_propeller}$

Now, when equation (4) is substitute with equation (7) and (8), a relational equation for $V_{drag_velocity}$ can be derived as in equation (9), which can be shown as Fig. 5.

$$\gamma = \frac{V_{drag_velocity}}{V_A} = 1 + \alpha(\sqrt{C_T + 1} - 1) \quad (9)$$

where, $\alpha = 0.105\{\log_{10} Rn_{mean} - 2.235\}\{\coth C_T + 2.512\}$

In conclusion, the drag of pod housing during the operation of propeller can be estimated via equation (1), (2), and (9).

Lastly, in order to estimate full scale performance for podded propeller more conveniently, drag of pod housing is normalized in the same way of thrust coefficient of propeller as in equation (10) using equation (2). Here, n and D is each rotation number and diameter of the propeller, $J(=V_A/nD)$ is advance ratio.

$$\begin{aligned} K_{D_pod_housing} &= \frac{R_{pod_housing_propeller}}{\rho n^2 D^4} \\ &= \frac{1}{2}(\gamma \cdot J)^2 \left(\frac{\sqrt{S}}{D}\right)^2 C_{D_pod_housing} \end{aligned} \quad (10)$$

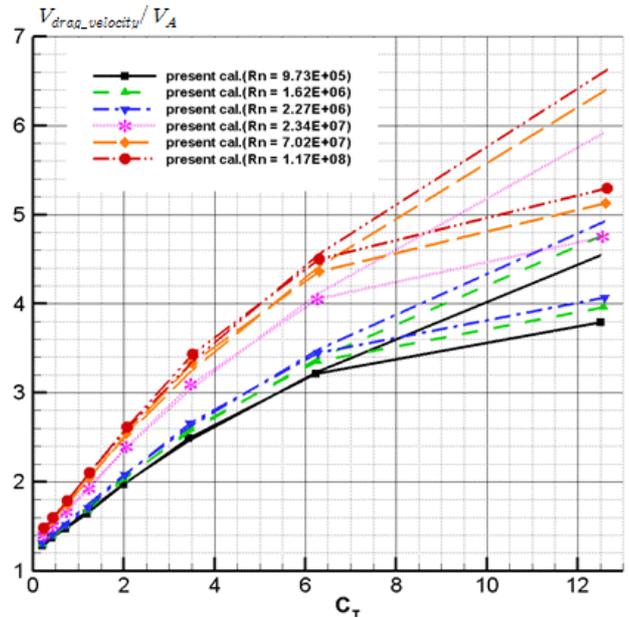


Fig. 5 Drag-velocity ratio from function

3 Estimation Method of Full Scale Performance for Podded Propellers

In the previous chapter, the method for deriving pod housing drag was suggested for estimating full scale performance for podded propellers.

In this chapter, the correction of thrust and torque of propeller blades regarding the interaction is discussed, and the procedures and methods for estimating full scale performance for podded propeller are suggested. Especially, through dynamometer for podded propeller, full scale performance method for each model test, open water test for propeller blades or pod housing is discussed. Also, estimation and evaluation process for the initial design stage before the model test is suggested as well.

3.1 General concept

The performance of podded propeller depends on thrust and torque, and since the torque of podded propeller and that of podded propeller unit are equal as mentioned in the appendix, the full scale performance can be estimated only with torque correction that considers interaction with pod housing. On the other hand, the thrust of podded propeller should be divided into thrust of pod propeller blades and pod housing drag in order to better estimate full scale performance for podded propeller through correction of thrust of propeller blades and extrapolation of pod housing drag. This concept is shown in Fig.6.

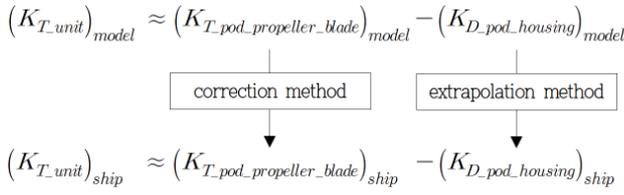


Fig. 6 General concept of estimation method of full scale performance for podded propeller

As shown in equation (11), the thrust of podded propeller blades can be assumed as the sum of thrust of the rotating blades only in open water and thrust increment due to their interaction with pod housing. Similarly, torque can be expressed as equation (12).

$$K_{T_{unit}} \approx K_{T_{pod_propeller_blade}} - K_{D_{pod_housing}} \approx (K_{T_{propeller_blade}} + \Delta K_{T_{interaction}}) - K_{D_{pod_housing}} \quad (11)$$

$$K_{Q_{unit}} \approx K_{Q_{pod_propeller_blade}} \approx K_{Q_{propeller_blade}} + \Delta K_{Q_{interaction}} \quad (12)$$

Therefore, the thrust and torque of podded propeller blades could be derived from those in open water considering the increment due to the interaction, and for the extrapolation to full scale, ITTC correction method can be applied like ordinary propellers. The force that acts between the fixed and rotating part of podded propeller is equal in size, but in opposite direction, thus not considered since it is assumed to be cancel out each other.

The effect of interaction with the pod housing is considered through defining the propeller blades in open water condition and the ratio of thrust and torque of podded propeller blades, as in equation (13), (14).

$$\Gamma_T = \frac{K_{T_{pod_propeller_blade}}}{K_{T_{propeller_blade}}} \quad (13)$$

$$\Gamma_Q = \frac{K_{Q_{pod_propeller_blade}}}{K_{Q_{propeller_blade}}} \quad (14)$$

The thrust and torque ratio of equation (13), (14) obtained from model test and numerical analysis are shown in Fig.7. In the case of numerical analysis, it includes the result of full scale Reynolds number as well.

In the case of model testing, torque of podded propeller and podded propeller blades could be assumed almost equal while thrust cannot be directly measured from podded propeller blades, except for the hub and cap, the thrust of podded propeller was used.

Thrust and torque ratio steadily increases along with the advance ratio and steepens at high advance ratio, but is shown to have almost no change against Reynolds number. In case of torque ratio, the results of model test and numerical analysis almost matches, and thrust ratio has small quantitative difference but shows similar tendency. Based on these, the increase of thrust and torque can be each considered with a polynomial expression as in equation (15), (16).

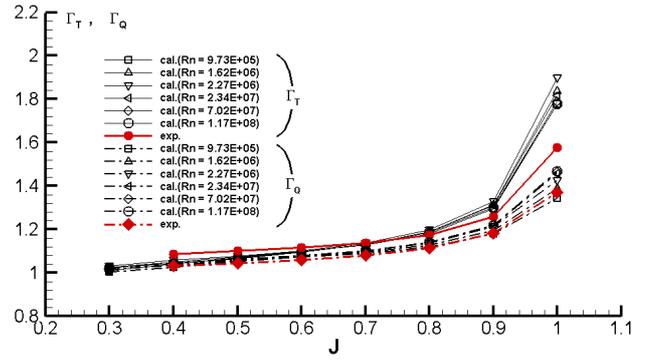


Fig. 7 Change of thrust and torque ratio according to advance ratio of podded propeller

$$\Gamma_T = 21.895 J^4 - 53.69 J^3 + 48.55 J^2 - 18.95 J + 3.78 \quad (15)$$

$$\Gamma_Q = 2.516 J^4 - 3.835 J^3 + 1.856 J^2 - 0.165 J + 0.989 \quad (16)$$

Meanwhile, the correlation between model and full scale should be known first, for extrapolation of pod housing drag of model to that of full scale

However, this requires information on drag of pod housing in full scale, and in reality there is no alternative other than numerical analysis.

Numerous studies has been done to derive pod housing drag using numerical analysis (Lobatchev and Chicherine, 2001; Sanchez-Caja et al., 2003; Chicherin et al., 2004), and especially Chicherin et al. (2004) pointed out that conventional form factor method is inappropriate since podded housing drag is influenced by podded propeller load and Reynolds number. They used RANS code to derive model-full scale drag coefficient ratio that holds constant value of pod housing drag.

In present study, pod housing model-full scale drag coefficient ratio(β) is adopted to be applicable according to propeller thrust load and Reynolds number through numerical analysis, which was used to estimate the pod housing drag. The relation between full scale and model pod housing drag is given as equation (17).

$$(K_{D_{pod_housing}})_{ship} = (K_{D_{pod_housing}})_{model} \cdot \beta \quad (17)$$

When equation (10) is applied to equation (17), it equals to equation (18).

$$\beta = \frac{(K_{D_{pod_housing}})_{ship}}{(K_{D_{pod_housing}})_{model}} = \frac{(\gamma^2 C_{D_{pod_housing}})_{ship}}{(\gamma^2 C_{D_{pod_housing}})_{model}} \quad (18)$$

As equation (18), drag velocity ratio is a function of thrust loading coefficient and Reynolds number, thus drag coefficient ratio β can be derived according to thrust loading coefficient and Reynolds number.

This result is shown in Fig.8. As Reynolds number increases towards full scale Reynolds number, β gets closer to 1. For all Reynolds number, it steadily increases

as thrust loading coefficient increases while it increases rapidly at lower thrust load. There are little differences in equation (18) and result of numerical analysis, but overall average error is 1.7%, which matches the tendency of Reynolds number and thrust load very well.

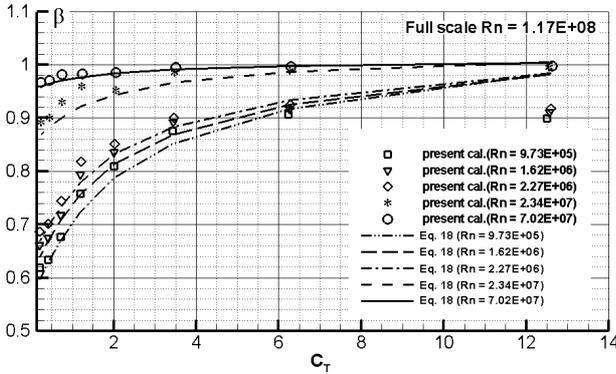


Fig. 8 Variation of model-full scale drag coefficient ratio with thrust loads for different Reynolds numbers

3.2 Estimation of Propulsive Performance in Full Scale Utilizing Dynamometer for Podded Propeller Unit

The thrust, torque of podded propeller, and thrust of pod unit is measured through model test since it can show thrust, drag and torque components as equation (19), (20).

$$(K_{T_{unit}})_{model} = (K_{T_{pod_propeller}})_{model} - (K_{T_{pod_stationary_part}})_{model}$$

$$= (K_{T_{pod_propeller}})_{model} - \left\{ (K_{T_{pod_propeller}})_{model} - (K_{T_{unit}})_{model} \right\} \quad (19)$$

$$(K_{Q_{unit}})_{model} = (K_{Q_{pod_propeller}})_{model} \quad (20)$$

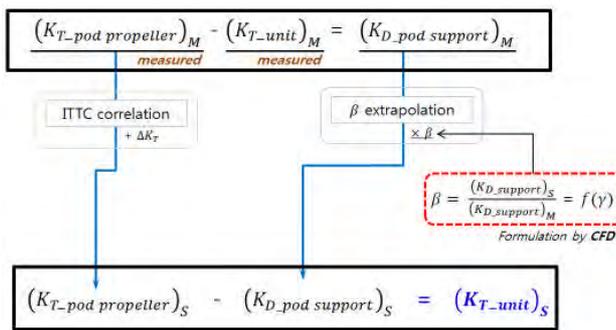


Fig. 9 Procedure and method for Estimation of Thrust of Podded Propeller Unit in Full Scale



Fig. 10 Procedure and method for Estimation of Torque of Podded Propeller in Full Scale

The method of full scale propulsive performance estimation can be derived easily due to the merit of being able to get thrust and drag directly from the test.

In case of model test, measurable drag factor ratio of fixed part of pod was used as drag factor ratio of pod housing, since direct measurement of pod housing drag is difficult. This can be shown as equation (21).

$$(K_{T_{unit}})_{ship} \approx (K_{T_{pod_propeller}})_{model} + \Delta K_{T_{propeller_blade_correction}} - \left\{ (K_{T_{pod_propeller}})_{model} - (K_{T_{unit}})_{model} \right\} \cdot \beta \quad (21)$$

Estimation procedure of full scale thrust and torque performance that utilizes the dynamometer for pod unit, is displayed as diagram in Fig. 9 and Fig. 10.

3.3 Full Scale Performance Estimation through The Result of Ordinary Propeller Open Water Test and Full Scale Performance Estimation at Early Design Stage.

When dynamometer for pod unit is not available, thrust change of propeller blade due to pod housing interaction and drag change of pod housing due to podded propeller cannot be derived directly from the tests.

Thus, performance of thrust and torque of propeller blade derived from individual propeller test, considering the interaction of equation (13), (14) it is possible to gain performance of thrust and torque of podded propeller. And in case of pod housing, drag can be gained from podded housing individual test, and using the drag velocity ratio of equation (9), and can derive drag of equation (2) that considered influence of podded propeller.

Thrust and torque of podded propulsor for model is available, and using the concept of Fig. 6, full scale performance can be estimated as (22), (23).

$$(K_{T_{unit}})_{ship} = (K_{T_{propeller_blade}})_{model} + (\Delta K_{T_{interaction}})_{model} + \Delta K_{T_{propeller_blade_correction}} - (K_{D_{pod_housing}})_{model} \cdot \beta \quad (22)$$

$$(K_{Q_{pod_propeller}})_{ship} = (K_{Q_{propeller_blade}})_{model} + (\Delta K_{Q_{interaction}})_{model} + \Delta K_{Q_{propeller_blade_correction}} \quad (23)$$

Based on this information, ordinary propeller open water test and full scale thrust or torque performance estimating process of podded propeller, that uses drag coefficient of podded housing, is shown in Fig. 11 and Fig.12.

Meanwhile, during the initial stage, before the stage of model testing, full scale propulsive performance estimation of podded propulsor could derive thrust and torque of propellers using affiliated propeller statistical data or potential code.

Also in the state where propulsor does not work, the drag ($C_{D_{pod_housing}}$) that applies to podded housing can

be derived through estimation equation, thus estimation of full scale performance of podded propulsor is possible.

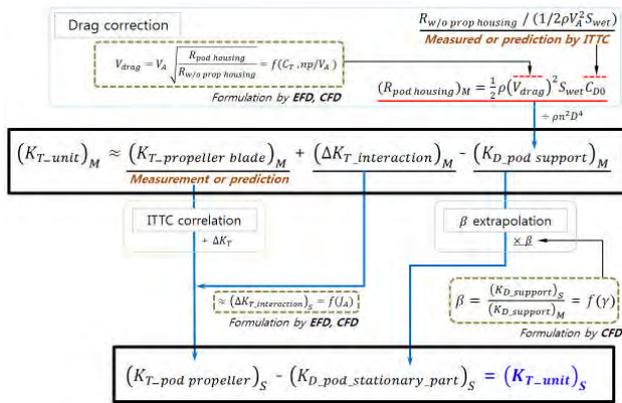


Fig. 11 Procedure for Estimation of Thrust of Podded Propeller Unit in Full Scale from Open Water Test

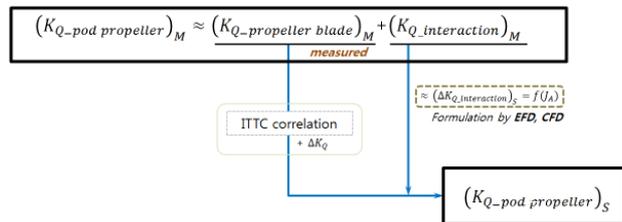


Fig. 12 Procedure for Estimation of Torque of Podded Propeller in Full Scale from Open Water Test

3.4 Verification and Evaluation of the Result

By using the present method, suggested in this paper, estimation of model and full scale performance of podded propulsor is compared with experiment and estimation data of other organizations.

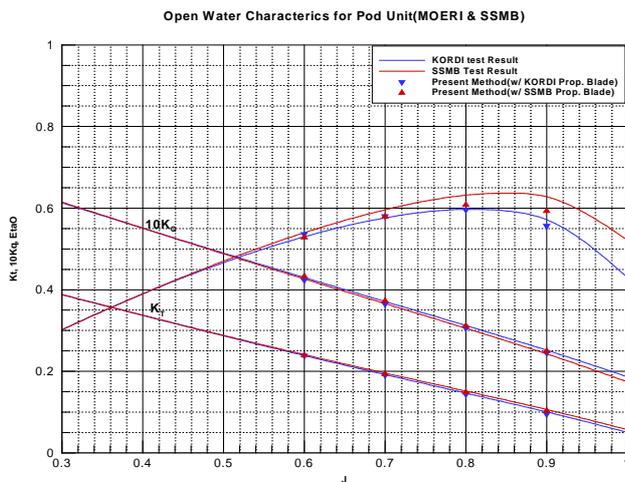


Fig. 13 Comparison of Estimations by Present Method in model scale

As shown in Fig. 13 ~ Fig.14, the full scale estimation result derived from this suggested method matches well with the thrust of pod unit, but torque is largely estimated, compared to the full scale estimation result of SSMB.

On the other hand, full scale estimation result of KORDI and this current suggested method matches from pod unit to torque of podded propeller.

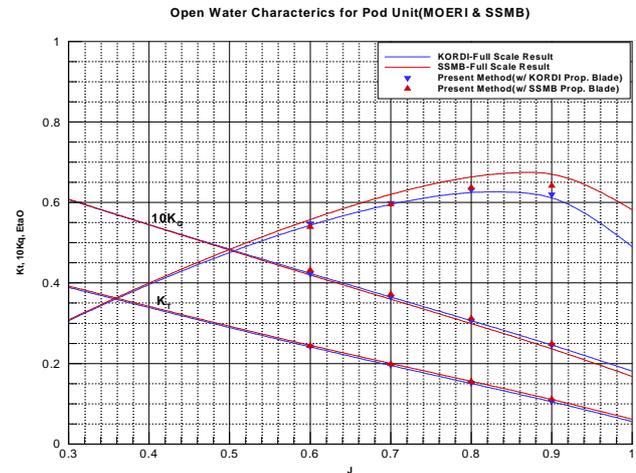


Fig. 14 Comparison of Estimations by Present Method in full scale

4 Conclusion

The conclusion of this study is as below

1. In order to estimate the drag of the pod housing resulted from pod propeller operation, a numerical model of drag velocity ratio that includes the loading of pod propeller and change in Reynolds number is suggested.
2. The drag coefficient ratio of pod housing for Model scale-Full scale is adopted, and the estimation method for full scale pod housing drag is suggested via deducting the change of drag ratio according to propeller loading and Reynolds number.
3. Thrust and drag components that affect the podded propulsor are decomposed, and hydrodynamic analysis is conducted to these components. By utilizing this accumulated data of the general propulsor, a new concept of performance estimation method, which makes it possible to estimate the performance of a podded propulsor even at the early design stage, is suggested.
4. By separating the thrust component of pod propeller and the drag component of pod housing, which act on the podded propulsor, application of the general concept of thrust correction and drag extrapolation was made possible. As a result, the foundation for the improvement of the design of pod propeller and pod housing as well as the performance enhancement was laid out.
5. As to the podded propulsor which has difficulty in performance estimation during the early design stage, accurate full scale performance estimation is now possible based on the open water characteristics of a general propeller. Also, even without a high-priced pod

dynamometer, performance estimation of podded propulsor is made possible based on the results of resistance test for the pod housing and open water test for the propeller blade only.

Henceforth, in order to procure the objectivity of the present estimation method of full scale propulsive performance, additional study on Reynolds number and wider scale of change in pod propeller loading is considered to be necessary. In addition, for the implementation on wider variety of podded propulsor, experimental and numerical study on the pod housing form with different dimension is necessary. Especially, hydrodynamic study on the drag of the pod strut, fin and their connections to the pod body is considered to be needed.

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APPENDIX

Definition of Force Components on Podded Propulsor(Fig. A-1, Fig. A-2, Table A-1)

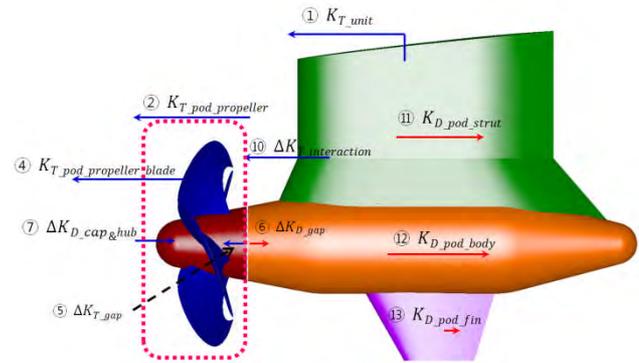


Fig. A-1 Forces on Podded Propulsor

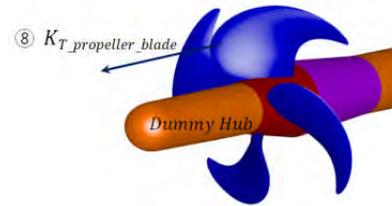


Fig. A-2 Thrust of Propeller blade in open water

$$\textcircled{1} = \textcircled{2} - \textcircled{3}$$

$$K_{T_unit} = K_{T_pod_propeller} - K_{D_pod_stationary_part} \quad (A-1)$$

$$\textcircled{3} = \textcircled{2} - \textcircled{1} = \textcircled{6} + \textcircled{11} + \textcircled{12} + \textcircled{13}$$

$$K_{D_pod_stationary_part} = K_{T_pod_propeller} - K_{T_unit}$$

$$= \Delta K_{D_gap} + K_{D_pod_strut} + K_{D_pod_body} + K_{D_pod_fin} \quad (A-2)$$

$$\textcircled{9} = \textcircled{7} + \textcircled{11} + \textcircled{12} + \textcircled{13} = \textcircled{7} + \textcircled{3} - \textcircled{6}$$

$$K_{D_pod_housing} = \Delta K_{D_cap\&hub} + K_{D_pod_strut} + K_{D_pod_body} + K_{D_pod_fin}$$

$$= \Delta K_{D_cap\&hub} + K_{D_stationary_part} - K_{D_gap} \quad (A-3)$$

$$\textcircled{5} = \textcircled{6}$$

$$\Delta K_{T_gap} \approx \Delta K_{D_gap} \quad (A-4)$$

$$\begin{aligned} \textcircled{1} &= \textcircled{4} + \textcircled{5} - \textcircled{7} - (\textcircled{6} + \textcircled{11} + \textcircled{12} + \textcircled{13}) \\ &\approx (\textcircled{8} + \textcircled{10}) + \textcircled{5} - \textcircled{7} - (\textcircled{6} + \textcircled{11} + \textcircled{12} + \textcircled{13}) \\ &\approx (\textcircled{8} + \textcircled{10}) - (\textcircled{7} + \textcircled{11} + \textcircled{12} + \textcircled{13}) \approx (\textcircled{8} + \textcircled{10}) + \textcircled{9} \end{aligned}$$

$$\begin{aligned} K_{T_unit} &\approx (K_{T_propeller_blade} + \Delta K_{T_interaction}) \\ &\quad - (\Delta K_{D_cap\&hub} + \Delta K_{D_pod_strut} + \Delta K_{D_pod_body} \\ &\quad + \Delta K_{D_pod_fin}) \\ &\approx (K_{T_propeller_blade} + \Delta K_{T_interaction}) - K_{D_pod_housing} \end{aligned} \quad (A-5)$$

$$\begin{aligned} \textcircled{4} + \textcircled{5} - \textcircled{7} &= (\textcircled{8} + \textcircled{10}) + \textcircled{5} - \textcircled{7} \\ K_{T_pod_propeller_blade} + \Delta K_{T_gap} - \Delta K_{D_cap\&hub} \\ &\approx K_{T_propeller_blade} + \Delta K_{T_interaction} + \Delta K_{D_gap} - \Delta K_{D_cap\&hub} \end{aligned} \quad (A-6)$$

$$\begin{aligned} K_{T_pod_propeller} &= K_{T_propeller_blade} + \Delta K_{T_interaction} + \Delta K_{D_gap} \\ &\quad - \Delta K_{D_cap\&hub} \end{aligned} \quad (A-7)$$

Definition of Torque Components on Podded Propulsor(Fig. A-3, Table A-2)

$$\begin{aligned} \textcircled{1} &= \textcircled{3} + \textcircled{4} + \textcircled{6} \approx (\textcircled{7} + \textcircled{9}) + \textcircled{4} + \textcircled{6} \approx \textcircled{7} + \textcircled{9} \\ K_{Q_pod_propeller} &= K_{Q_pod_propeller_blade} + \Delta K_{Q_gap} + \Delta K_{Q_cap\&hub} \\ &\approx (K_{Q_propeller_blade} + K_{Q_pod_housing}) + \Delta K_{Q_gap} + \Delta K_{Q_cap\&hub} \\ &\approx K_{Q_propeller_blade} + \Delta K_{Q_interaction} \end{aligned} \quad (A-8)$$

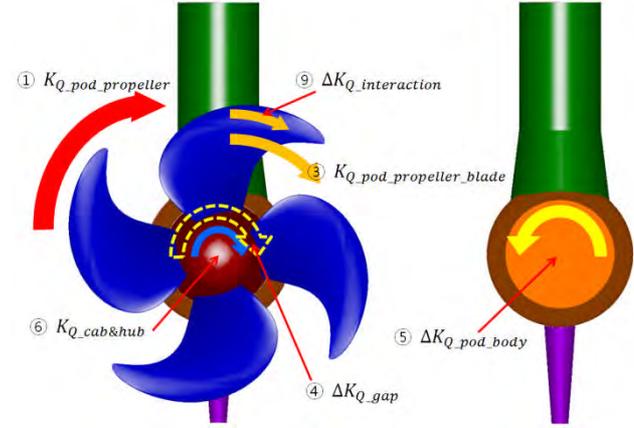


Fig. A-3 Torques on Podded Propulsor

Table A-1 Definition of Thrust and Drag components on Podded Propulsor

No.	Nomenclature	Definition
①	K_{T_unit}	Net thrust of the Pod Unit – measurable(= ②-③)
②	$K_{T_pod_propeller}$	Thrust component of the rotating part of the Pod Unit – Measurable(= ④+⑤-⑦)
③	$K_{D_pod_stationary_part}$	Drag component of the stationary part of the Pod Unit(= ②-① = ⑥+⑪+⑫+⑬)
④	$K_{T_pod_propeller_blade}$	Thrust of the Pod Propeller blade(≈ ⑧+⑩)
⑤	ΔK_{T_gap}	Thrust component of rotating part of the gap between rotating and stationary part of the Pod Unit(≈ +⑥)
⑥	ΔK_{D_gap}	Thrust component of stationary part of the gap between rotating and stationary part of the Pod Unit (≈ -⑤)
⑦	$\Delta K_{D_cap\&hub}$	Drag component on pod propeller cap and hub
⑧	$K_{T_propeller_blade}$	Virtual thrust on propeller blades in open water
⑨	$K_{D_pod_housing}$	Virtual drag on pod housing with pod propeller acting(≈ ③-⑥+⑦ ≈ ⑦+⑪+⑫+⑬)
⑩	$\Delta K_{T_interaction}$	Thrust increase component of propeller blades due to interaction between pod propeller and pod housing
⑪	$K_{D_pod_strut}$	Drag component on the strut with pod propeller acting
⑫	$K_{D_pod_body}$	Drag component on the pod body with pod propeller acting
⑬	$K_{D_pod_fin}$	Drag component on the fin with pod propeller acting

Table A-2 Definition of Torque components on Podded Propulsor

No.	Nomenclature	Definition
①	$K_{Q_pod_propeller}$	Net torque of rotating part of the pod unit(= ③ + ④ + ⑥)
②	$K_{Q_pod_stationary_part}$	Net torque of stationary part of the pod unit(= -①)
③	$K_{Q_pod_propeller_blade}$	Torque on pod propeller blades(≈ ⑦ + ⑨)
④	ΔK_{Q_gap}	Torque component of rotating part of the gap between rotating and stationary part of the Pod Unit (≈ +⑤)
⑤	$\Delta K_{Q_pod_body}$	Torque component of stationary part of the gap between rotating and stationary part of the Pod Unit (= -④)
⑥	$K_{Q_cab\&hub}$	Torque component on pod propeller cab and hub
⑦	$K_{Q_propeller_blade}$	Virtual torque on propeller blades in open water
⑧	$K_{Q_pod_housing}$	Virtual torque on pod housing with pod propeller acting
⑨	$\Delta K_{Q_interaction}$	Torque increase component of propeller blades due to interaction between pod propeller and pod housing