Modeling of full-scale propeller characteristics at the life cycle initial stages of marine systems

Aleksey Yu. Yakovlev, Thant Zin
St. Petersburg state marine technical University, Lotmsanskaya, 3, St. Petersburg, 190121, Russian Federation

kgm@smtu.ru

Abstract. Modeling of full-scale propellers characteristics at the design stage is one of the actual practical tasks. A method has been developed for converting characteristics from the model to nature to solve this task. The method is based on modeling the propeller operation using Eduard Papmeln modified method. The boundary layer characteristics are calculated for the blades cylindrical sections and the axisymmetric body modeling the hub. Compliance between the evaluation characteristics and a model tests result is ensured by selecting a number of parameters that take into account the features of the flow around the blades and the incoming flow.

Introduction
The following stages of the life cycle can be distinguished for marine systems, by analogy with the General approach: research and justification of development, development, production, operation, major repairs, and disposal. In modern conditions, special attention is paid to the first two of these stages for complex science-intensive products and systems. Moreover, the design is carried out iteratively, in this case. Which allow avoids serious errors. Modeling methods play a key role in the first two stages. These methods may be calculating or based on a model experiment, but in any case they must ensure that the intended characteristics are achieved during the operational phase. In other words, designers should be able to anticipate the characteristics of the systems being developed in advance.

This problem is relevant for all industries, but it is especially acute in the shipbuilding industry [1]. Because the size and complex operating conditions of real marine systems are almost impossible to reproduce in model conditions. The so-called scale effect problem takes place in this case from the classical mechanics point of view. The scale effect is traditionally understood as the difference between the dimensionless characteristics of a model and a full-scale object. It appears due to violation of the mechanical similarity conditions.

Thus, it is not enough to have the results of model tests to obtain the characteristics of a real full-scale object. You still need to be able to correctly recalculate them to full-scale dimensions and operating conditions. Currently, there are internationally standardized conversion methods (ITTC ’78). However, these methods do not always suit designers. Scaling methods are being actively developed for this reason to determine the characteristics of a full-scale object based on the results of model tests.
1. Problem statement
The development of methods for the scale effect accounting is a separate task that stands apart from model tests and hydrodynamic calculations. The scale effect account combines the tools used in experimental and computational methods. But first of all it requires theoretical modeling the features of the mechanical processes taking place.

The specific requirements are made for scale effect accounting since it is a practical task. Such requirements for the method of propellers scale effect accounting are formulated in [2]:

- Independence on the Reynolds number of the model test. That means the Reynolds number of model tests should not affect the full scale characteristics of the propeller.
- Independence of the propeller geometry. The accuracy of the scale effect accounting should not depend on the features of the propeller geometry.
- Absolute accuracy. Full-scale characteristics should be determined directly based on the results of model tests, using corrective coefficients.
- Reliability. The method may be used as a tool for analyzing the reliability of model test results.

We can distinguish the following schemes for the propellers scale effect accounting based on the Helma systematization [2], [3]:

- The scale effect neglecting. This approach gives an approximation with a margin. That is, the designer knows that the full-scale propeller will be better than the forecast obtained on the basis of model tests. But same time he does not know how much better.
- Methods based on the use of computational fluid dynamic (CFD) calculation of full-scale propeller characteristics. This technique was proposed at the early stage of modern CFD methods development, but it has not become a practical designer tool until now. The fact is that it is extremely difficult to justify the compliance of the CFD-method with the helm criteria listed above. The results of recalculation depend on the calculation grid used, the turbulence model, and flow parameters. Moreover, it is impossible to perform a direct recalculation of the results of model tests. However, many experts believe that in the future, the scale effect accounting will be based on CFD-methods [4] [5].
- Methods based on the analysis of the flow around a character propeller blade section that simulates the operation of the propeller as a whole. This approach fully meets all the Helma criteria. It ensures the simplicity and practical effectiveness of the method, but at the same time does not allow us to take into account the nonlinear effects associated with changes in the flow around the blade at different radii. This approach is the base for the classical ITTC’78 method [6], the Lehrbs-Meyne method [7], and one of the modern methods, the $\beta$-method [2].
- Methods based on the analysis of the flow along the propeller blade cylindrical sections. These methods also meet all the Helma criteria. Theoretically it should provide a better feature analysis of the flow around blades, taking into account nonlinear effects. The [8] method and the [9] method are implemented using this principle. The disadvantages of these methods include the assumption that the flow along blade cylindrical sections, which is actually not always true, especially in model conditions.

To solve practical problems, it was decided to develop an improved method for propeller scale effect accounting, based on the analysis of flow around blade cylindrical sections. The method improvements relate primarily to the features of the scale effect accounting, which are described below.

2. Main principles of scaling
Ship hulls, marine equipment objects, their protruding parts and propellers have a complex shape. The shape, as a rule, can be represented as a combination of simple basic elements. These elements include the airfoil sections and the bodies of revolution. So if it were developed scaling methods for airfoils and bodies of revolution, it is possible to develop scaling methods for more complex objects. It is important that these methods have a few free empirical parameters. It allows configure the mathematical model to get the compliance with the available model experimental data. The theoretical
relations model in this case the dependence of the hydrodynamic characteristics on the similarity numbers.

The key similarity number, which is primarily associated with the scale effect in hydrodynamic, is the Reynolds number:

\[ Re = \frac{V_\alpha C}{\nu} \]  

(1)

Where: \( V_\alpha \) – inflow velocity, \( C \) – linear size (airfoil chord length, propeller diameter, etc.), \( \nu \) – the viscosity coefficient.

It is assumed follow that there are model tests results for Re values in the range \( 10^3 - 10^6 \). It is necessary to evaluate based on these data the hydrodynamic characteristics for large Reynolds numbers of order \( 2 \times 10^6 - 10^7 \) and higher.

2.1. Scaling method for airfoils

The method was developed earlier and presented in [10]. The boundary equations method (BEM) is used to calculate the flow around the airfoil, to get a solution in an inviscid liquid. The relations obtained on the basis of the boundary layer theory are used to account the processes caused by the liquid viscosity. The airfoil resistance coefficient is determined based on the Squire-Young formula [11]. The pulse loss thickness is determined during the boundary layer calculation and then substituted to the Squire-Young formula. The boundary layer is calculated using the common integral relations [11], taking into account the laminar-turbulent transition (in the plane formulation) and the development of a separation flow. The airfoil lift coefficient is determined based on the BEM calculation with introduction of a special correction factor \( \Delta \alpha \). The factor is determined based on the boundary layer calculation. It depends on the angle of attack \( \alpha \) and the Reynolds number.

The implemented design scheme contains free parameters \( (f^{\*}\_0, \varepsilon^*, L_s, \sigma) \) that should be determined by comparison with model test data [10]. The values \( f^{\*}\_0, \varepsilon^* \) affect the beginning of the laminar-turbulent transition. They are choiced to get matching the calculated dependence of the profile resistance coefficient on the Reynolds number with experimental data at zero airfoil angle of attack. The parameters \( L_s \) and \( \sigma \) used to coordinate the calculation with the model experiment in the separation flow area. Moreover, the \( L_s \) parameter has a noticeable effect on the value of the critical angle of attack. Thus the calculation method is adjusted by selecting the parameters \( f^{\*}\_0, \varepsilon^*, L_s \) and \( \sigma \). You can perform calculations for full-scale Reynolds numbers when parameter values are fitted.

2.2. Scaling method for bodies of revolution

The method is presented in [12]. The pressure distribution on the body of revolution is determined using the special BEM for nonuniform flow around axisymmetric bodies. We use for the boundary layer calculation the transition from the axisymmetric task to a flat boundary layer problem [13]. One may apply by this way all developments made earlier for airfoils [10] to bodies of revolution. An analog of the Squire-young formula for axisymmetric bodies is used to calculate the resistance of a body of revolution.

The scaling parameters, as previously was set for airfoils, are the parameters included in the calculation method presented above and determined by fitting the calculation results with model test data. These parameters for bodies of revolution include \( f^{\*}\_0, \varepsilon^*, \sigma \) and \( \alpha \) values. The values \( f^{\*}\_0, \varepsilon^* \) are similar to the case of flow around flat airfoil considered above. The value \( \alpha \) takes into account the effect of the velocity at the tail end on the body's resistance. The more significantly the velocity differs from the incoming flow velocity, the stronger the influence. The role of the parameter \( \sigma \) is to take into account small areas of separation flow in the tail part of the bodies of revolution. The process of scale effect account is generally similar to the airfoil case. The calculation method is adjusted by selecting parameters, and after the adjustment is made, the calculation can be performed for full-scale Reynolds numbers.
3. Propeller calculation method

The method used for modeling the propeller operation [14] is a modified method of Eduard Papmel [15].

The hydrodynamic forces are determined by the stripes formed by blade cylindrical sections within the framework of this method. Propeller thrust and torque determine by integrating this forces. Figure 1 shows a straightened blade stripe with a width of dr and a diagram of velocities and hydrodynamic forces.

![Diagram of velocities and hydrodynamic forces](image)

**Fig.1.** Straightened cylindrical stripe of the propeller blade, diagrams of velocities and hydrodynamic forces

$C$ – chord length, $r$ – radius, $\beta$ – angle of advance ratio, $\beta_i$ – angle of inductive advance ratio.

The angle of attack of the cylindrical section $\alpha$ and the inflow velocity $W_i$ depend on the velocity of propeller movement $V_x$, rotation velocity of propeller $\Omega=2\pi n$ (where $n$ is the number of propeller revolution) and the induced velocities caused by the operation of the propeller

$$W_i = \sqrt{(V_x + w_x)^2 + (\Omega r + w_\tau)^2}$$

where $w_x, w_\tau$ - the axial and tangential induced velocities in the propeller disk, the radial velocity component is not taken into account.

The induced velocities in the propeller disk are defined as follows

$$w_x = V_x \frac{A}{1-A}, \quad w_\tau = \Omega r \frac{B}{1-B}$$

$$A = \frac{Z C_L \cos \beta_i - C_D \cdot \sin \beta_i}{8 \pi r K_Z \sin^2 \beta_i}$$

$$B = \frac{Z C_L \cdot \sin \beta_i + C_D \cdot \cos \beta_i}{8 \pi r K_Z \sin \beta_i \cos \beta_i}$$

Where: $C_L, C_D$ – the coefficients of lift and drag, and $K_Z$ - the Goldstein correction for the finiteness of the number of blades, $Z$ – number of propeller blades.

It is necessary to know the value of the angle $\beta_i$ to unambiguously determine the induced velocities. This value may be obtained by solving the equation that follows from the velocity triangle (Fig. 1).

$$\text{ctg} \beta_i = \frac{\Omega r - w_\tau}{V_x - w_x}$$
This is a nonlinear algebraic equation. Angle of inductive advance ratio $\beta_i$ is unknown value. Equation is solved by the method of successive approximations.

To obtain the force and moment acting on the propeller, you must perform the described procedure for a number of cylindrical stripes of the blade and integrate the forces along the radius. Its would be written in dimensionless form by the next way.

\[
K_T = \frac{Z J^2}{8} \int_{r_0}^1 C_{L} \overline{C_l} W_{i}^2 \cdot \cos \beta_i (1 - \varepsilon \cdot tg \beta_i) d\bar{r}
\]
\[
K_Q = \frac{Z J^2}{16} \int_{r_0}^1 C_{L} \overline{C_l} W_{i}^2 \cdot \sin \beta_i (1 + \varepsilon \cdot c tg \beta_i) \bar{r} d\bar{r}
\]

Where: $r_0$ - radius of the hub, $\varepsilon = \frac{C_D}{C_L}$ - the inverse quality coefficient of the profile. The velocities indicated by the dash at the top are related to the propeller movement speed. The dash over the linear values mean de-dimensionalization by propeller radius $R$.

One can conclude analyzing the expression (5) that the accuracy of the propeller thrust and torque estimation depend on the accuracy of the lift and drag coefficients. In the original method, these values are determined on the basis of common relations, including Mishkevich's empirical formulas [16]. Now, the method presented above for the airfoils is used to calculate the lift and drag coefficients of cylindrical section stripes [10] instead of those formulas.

4. Scaling of propeller characteristics

4.1. Parameters of scaling

Scaling parameters are understood as previously for profiles [10] and axisymmetric bodies [12] as parameters included in the calculation method and determined by comparison with model test data. They should be determined from the condition of matching the calculation results with model experimental data.

These parameters can include $f^*_0$, $\varepsilon^*$, $L_s$ and $\sigma$ introduced above for the profiles [10], as follows from the description of the calculation method presented above. The values $f^*_0$ and $\varepsilon^*$ influence the moment of the laminar-turbulent transition so they may inflay on the propeller characteristics seriously. The parameters $L_s$ and $\sigma$ should be used in case of separation flow. So values $L$ and $\sigma$ can be ignored when taking into account the scale effect for a propeller operating near the design mode since the propeller blades usually work in the first quadrant in the absence of flow separation.

It is much more important to take into account three-dimensional effects when modeling the operation of the propeller blades. Such effects are associated with the deviation of flow lines from the cylindrical sections and the influence of the complex shape of the free vortex sheet behind the blades. It was offered to get account for these features the coefficients $a$ and $b$ in the Goldstein corrections (3) are also proposed to be considered as scaling parameters. The first parameter allows us to take into account the difference between the actual induced velocities and their theoretical estimations (3), and the second parameter takes into account the difference of the experimental induced velocities distribution along the radius from the theoretical one.

The full-scale propeller is calculated using the method presented above with the scaling parameters configured for the specified results of model tests. The method of scale effect accounting for the bodies of revolution allows us to take into account the contribution of the propeller hub.

4.2. Sample of propeller characteristics scaling

As an example, consider the P1374 propeller. The geometry of this propeller has been presented in a number of publications, for example [17]. The paper [18] presents the results of scale effect estimating for P1374 propeller in free water and as part of a podded propulsor. The estimation method used in
that paper based on CFD calculations. The scale effect evaluation by ITTC’78 method [6] is presented in [18] additionally.

Corrections for the thrust and torque coefficients of P1374 propeller were calculated using the method presented in this paper. The model data and the full scale parameters were taken from [18]. The corrections are compared with calculation [18] and ITTC’78 method evaluations (fig. 2, 3). The values of corrections presented on the figures depending on the propeller load $C_{TH}$ (similar to [18])

$$C_{TH} = \frac{8}{\pi} \left( \frac{nD}{V_s} \right)^2 K_T$$

Where $D=2R$ – propeller diameter.

Corrections $dK_T$ and $dK_Q$ has been presented in percent of the model scale values $K_T$ and $K_Q$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Scale effect corrections for the thrust coefficient of P1374 propeller. 1 – ITTC’78 method, 2 – CFD-calculation [18], 3 – present method.}
\end{figure}

The first conclusion from the comparison is the corrections evaluated by present method have the same trends as corrections of ITTC’78 method. Both methods give the same signs of corrections and similar trends of their growth with a propeller load decrease. The presented method tends to smaller values of corrections values, which is especially noticeable for the moment coefficient. As a result, we can expect less optimistic estimates of the efficiency increase for a full-scale propeller in comparison with the ITTC’78 method.

The second conclusion concerns comparison with CFD calculations. The estimates obtained by full-scale CFD calculation [18] differ strikingly from present calculation and from the forecast of the ITTC’78 method too. It is impossible to draw final conclusions in the absence of a direct experimental assessment of scale effect. But the ITTC’78 can be considered as practical standard because it is based on the processing of experimental data. From this point of view the presented simplified method is more suitable for solving practical tasks than more complex CFD methods.
Fig.3. Scale effect corrections for the torque coefficient of P1374 propeller.
1 – ITTC’78 method, 2 – CFD-calculation [18], 3 – present method.

Conclusion
Summing up we can highlight the main results of the work:

- A method for the propellers scale effect accounting has been developed. The method is based on a modified Eduard Papmell method and previously developed methods for scale effect accounting of the airfoils and axisymmetric bodies.
- A good agreement has been demonstrated between the results obtained using the developed method and the results of the ITTC’78 method which based on experimental data processing.
- The presented method can be used to evaluate the full-scale propeller characteristics at the stages of research and development of marine systems. Its advantages are operating speed and a small amount of source data.

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