

Calculation of propulsion pod characteristics in off-design operating conditions

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ABSTRACT

The paper presents a method providing fast and sufficiently accurate estimation of propulsion pod characteristics in off-design operating conditions. The method takes the benefit of simple and prompt calculation procedures coupled with the use of available systematic model test data.

The methodology includes calculations of propeller in strongly oblique flow conditions, estimation of forces on the pod and account of overall propeller/pod interaction.

The propeller characteristics in strongly oblique flow conditions is calculated using strip theory assumptions. For evaluation of propulsor characteristics at large flow angles or extreme advance coefficient values the methodology includes the analysis of flow separation inception and transition to separated flow conditions of propeller blade operation. The analysis of separated flow conditions is performed using the Rayleigh approach. Similar principles are applied for calculation of flow conditions around the propulsion pod.

Model test data were analyzed to obtain practical estimates. Based on these data the coefficients were obtained to take into account the evolution of flow separation phenomena and propeller/pod interaction. These efforts resulted into an empirical calculation method providing accurate and fast evaluation of pod characteristics in off-design operating modes.

Keywords

Propulsion pods, off-design operating conditions, calculation method.

1 INTRODUCTION

For successful ship design it is required to know propulsor characteristics including those in off-design operating conditions. Propeller characteristics are usually determined based on model test results. Experimental studies for propulsion pods involve much more labor-consuming and costly efforts. Also, unlike propellers the propulsion pods include not only propulsor itself but also control actuators. From practical experience it is known that in many cases operation of propulsion pods in off-design modes prove to be no less important. These operating conditions, for example, acquire primary importance in case of ship maneuvering, turning and crash stop.

The requirement to estimate propulsor performance in off-design conditions presents a much more challenging task for calculations. Usually, the task for the design mode is to ensure separation-free flow conditions at the lowest flow drag losses. Most of the calculation methods are focused on simulation of such flow conditions. Unlike these methods the task of this paper is to formulate a procedure for calculating hydrodynamic performance of the propulsion pod in off-design conditions. The emphasis is made on the possibility to use this method in the development of propulsor itself.

Earlier investigations of similar type were performed for propellers. It should be noted that these studies were focused on two specific areas: calculation of propeller in reversing mode and calculation of propeller in oblique flow. One of the well-known vertex-theory method of propeller calculation for the reversing mode is presented in the paper by Rusetsky and Prischemihina (1981). The above-mentioned paper and the book by Basin and Miniovich (1963) contain reviews of earlier theoretical studies in this field. The task of hydrodynamic calculations for propeller at large incident flow angles (from 0 to $\pm 90^\circ$) within the framework of lifting-surface theory was addressed in the papers of Efimova et al (1988a, 1988b). The methods proposed in these papers make it possible to obtain results in good agreement with experimental data. The numerical method of Bavin, Lipis and Moukhina (1984), which implements this approach, is based on the vortex surface theory with non-linear elements because the method of successive approximation is used when the vortex sheet is trailing downstream of the propulsor. The modern concepts of propeller calculation in off-design modes are presented in the papers by Chen & Stern (1999) for RANS method application, Krasilnikov et al (2005) for the controllable pitch propellers and in the paper by Mukhina and Yakovlev (2001) for propeller operating in oblique flow.

Unlike the above-mentioned methods the calculations of propulsion pods have to cover a wide range of flow angles (from 0 to 360 deg.) and possibility of negative advance ratios. The above-mentioned methods are not intended for calculation of such operating modes.

Calculation of ship stopping maneuvers performed by means of propulsion pods and estimation of forces on propeller and pod arising in the reversing mode are

covered in (Woodward et al 2005). This paper presents the method for extrapolation of propeller quasi-reversing data to oblique flow operating conditions including propeller/pod interaction as well as empirical formulas for estimation of force arising on the propulsion pod due to pod rotation. As compared to the method presented in (Woodward et al 2005) the method of this paper allows us to directly calculate propeller characteristics simultaneously take into account the changes in advance ratio and angle of pod. It is based on the results and relationships obtained from processing the pod model test data, which significantly enhances the method's accuracy.

2 TASK FORMULATION

The pod characteristics are presented using pod-fixed rectangular and cylindrical coordinate axes (Fig. 1). Rotation of pod with respect to incident flow velocity V is defined by angle ψ . The paper addresses the propulsion pods of pulling type, therefore, zero value of angle ψ corresponds to the design propeller position forward of the gondola.

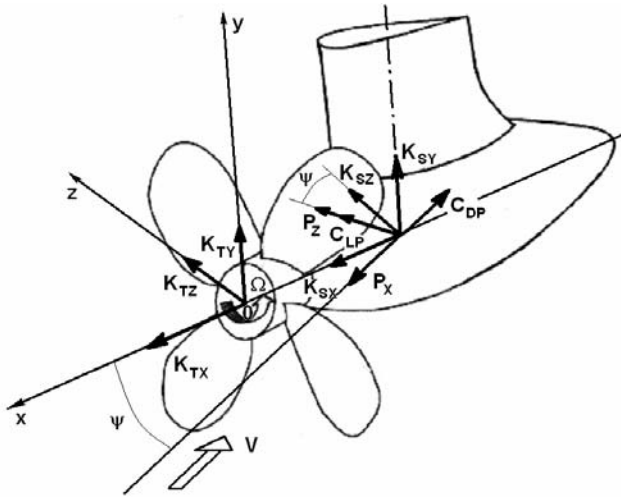


Fig. 1. Pod layout and coordinate axes.

In view of the above stated practical focus, the calculation method under consideration is designed to provide reliable estimates of forces and moments acting on the propulsion pod and its propeller at an arbitrary angle of pod rotation within the realistic range of advance ratios. The actual advance ratios include small advance ratios around the bollard pull point corresponding to ship mooring maneuvers and advance ratios typical of emergency maneuvers.

The main results of these calculations are longitudinal and transverse components of non-dimensional force K_T and moment K_Q of propeller, forces on pod K_P (indicated by subscript P) as well as the total force K_S (indicated by subscript S), which are presented in the pod-fixed coordinate axes. The forces are referred to $\rho n^2 D^4$, while the moments are referred to $\rho n^2 D^5$. Where: D – propeller diameter, n – number of revolution. The component forces acting along P_X and across P_Z directions of incident flow can be found by summation of

projected longitudinal K_X and transverse K_Z components of any of these forces.

$$\begin{aligned} P_X &= K_X \cdot \cos(\psi) - K_Z \cdot \sin(\psi) \\ P_Z &= K_X \cdot \sin(\psi) + K_Z \cdot \cos(\psi) \end{aligned} \quad (1)$$

Propeller characteristics in design modes are usually calculated by vortex-theory and boundary-element methods. In Russia it is common to introduce corrections for viscosity allowing the use of calculation results for practical estimates. The most widely used corrections in ship design are corrections of V.G. Mishkevich (Bavin et al 1983), which are successfully employed until now. These corrections are used not only for propellers but also for estimating the characteristics of pods at small angles of deflection (Achkinadze et al 2003), (Yakovlev 2008).

However, off-design conditions call for special calculation methods. Since the vortex theory application would inevitably require substantial assumptions and CFD techniques would involve labour-consuming procedures, a new method was developed on the basis of propeller strip theory and a number of empirical relations obtained from analysis of experimental data.

3 METHOD FOR CALCULATING FORCES ON BLADE SECTIONS

In propeller calculation by strip theory it is required to know the lifting force coefficient C_L and drag coefficient C_D of cylindrical blade sections introduced in a traditional way

$$C_L = \frac{2F_L}{\rho V^2 C}, \quad C_D = \frac{2F_D}{\rho V^2 C}$$

where F_L , F_D – respective dimensional force components, C – blade width, ρ – fluid density.

For off-design propeller calculations it is required to invent a method for calculating these characteristics in a wide range of incidence angles.

In accordance with (Bavin et al 1983), at small incidence angles α the lifting force coefficient is conveniently represented as a sum of lifting force coefficients in ideal fluid C_{LI} and corrections ΔC_L for viscosity effects.

$$C_L = C_{LI} + \Delta C_L \quad (2)$$

The value of correction ΔC_L can be found if we know the derivative of lifting force coefficient with respect to incidence angle and zero lift angle α_{0l} in ideal fluid. These values as well as the coefficient C_{LI} are obtained by calculations for non-viscous fluid. Equation (2) is valid for linear relationship of C_L and incidence angle.

In accordance with the methodology (Bavin et al 1983) the coefficient C_D is independent of incidence angle, which significantly limits the range of its application as compared to C_L . In the examined problem the coefficient C_D is determined using the Squire-Young formula (Elizarov et al 1994) relating C_D to the momentum thickness at trailing edge.

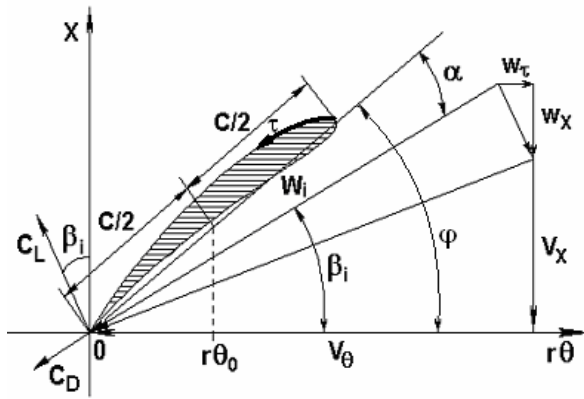


Fig.2. Calculation of blade section forces.

Within the framework of the assumptions made the momentum thickness can be obtained by integrating the exponential function of velocity on blade section surface (Elizarov et al 1994). Assuming that the blade section thickness is infinitely small one can perform integration over the chord rather than surface. Substitution of the integration result into the Squire-Young formula gives the relationship of drag coefficient C_D versus Reynolds number and velocity on blade section surface. If we sum up the resistance due to flow around back and face surface of the blade section we get the following relation for the drag coefficient

$$C_B = \frac{0.0306}{Re^{\frac{1}{7}}} \sum_{j=1,2} \left[\int_0^1 |\bar{V}_j(\tau)|^{3.54} d\tau \right]^{\frac{6}{7}} \quad (3)$$

where $\bar{V}_j(\tau)$ - velocity on blade section related to incident flow velocity V , τ - chordwise distance from blade tip referred to blade section length C , $j=1$ corresponds to back side, while $j=2$ corresponds to the blade face.

Formula (3) can be used to estimate the drag coefficient at sub-critical incidence angles if the velocity distribution on blade section surface is known. This distribution can be obtained by the ideal-fluid calculations. Analytical verification has indicated that at small lifting force coefficients the derived relation is similar in structure and coefficient values to the C_D formula introduced in (Bavin et al 1983). At the same time relation (3) is valid for the same range of incidence angles as relation (2).

All relations given above are valid for separation-free flow conditions. However, in reality when the angle of blade section incidence exceeds some critical value α_{cr} we observe flow separation phenomena. It results in a principally different flow pattern around the blade section, so it is impossible to use the same formulas for the drag and lifting force coefficients applicable to separation-free flow case.

It is difficult to predict when exactly the flow starts to stall from the blade section and this task requires special calculations. For simplified estimations of critical incidence angle of stall the following assumptions are

made: blade sections are assumed similar to NACA66, the flow is assumed turbulent at any point of the blade section and the laminar flow effect at the tip is ignored.

The stalling point is determined following recommendations of (Elizarov et al 1994). Taking into account the above assumptions the stalling point is found by satisfying the following condition for the parameter $f(\tau^*)$.

$$f(\tau^*) = \frac{7}{6} \frac{1}{|V(\tau^*)|^{4.54}} \frac{dV}{d\tau} \int_0^{\tau^*} |V(\tau)|^{3.54} d\tau < -3 \quad (4)$$

where τ^* - coordinate τ corresponding the stalling point.

By integration of (4) one can relate the stalling point to some limiting value of the lifting force. This lifting force limit is achieved at some incidence angle to be assumed as critical α_{cr} . If the blade section incidence is increased above the critical angle α_c , a stagnant zone is formed behind the blade section characterized by nearly constant pressure as it is usually assumed (Czhen 1972). In this case the blade section characteristics change drastically. It is advisable to apply the ideal fluid strip theory for their evaluation.

Under this theory the Rayleigh formula is used to determine the coefficient of normal force on flat plate with separating flow jets (Gurevich 1979).

$$C_N = C_0 \cdot \frac{2\pi \sin(\alpha)}{4 + \pi \sin(\alpha)} \quad (5)$$

where C_N - normal force coefficient obtained by the same reduction procedure as C_L и C_D , C_0 , i.e. referred to the factor taking into account the pressure in stagnant zone.

Since a thin blade section at high incidence angles is subject to the same flow conditions as a plate, the Rayleigh formula can be used to estimate the force acting on the blade section under separated flow conditions. However, as it was shown in practice without special selection of C_0 values the Rayleigh formula significantly underestimates the force, while the type of dependence the force has on the incidence angle is predicted correctly with this formula. For obtaining the force value applicable for practical estimates let us use the relation for C_0 which was introduced in (Gurevich 1979).

$$C_0 = 1.0 + \sigma + \frac{\sigma^2}{8(\pi + 4)} \quad (6)$$

where σ - pressure coefficient corresponding to the stagnant zone pressure.

The value σ may be other than zero if the separated flow area does not extend to infinity, as assumed in derivation of the Rayleigh formula (5), but closes at finite distance from the blade. Pressure σ will depend on the blade section incidence and shape. Let us assume for propeller blades the relation of σ which approximates the test data of flat plate.

$$\sigma = 1.5209 \cdot \sin(\alpha) + 0.1667 \cdot \sin(3\alpha)$$

All the above considerations refer to calculation of 2D blade sections. However, separated flow conditions around a foil of finite span are different from the separated flow around 2D blade section. Considering small elongation of blades a correction factor κ is introduced for evaluation of the force arising under separated flow pattern around blades.

Below we consider an example of calculations of blade section No.7 from (Miniovich 1958). Fig. 3 compares analytical and experimental data obtained for this blade section. It is seen that the blade section characteristics under separation-free flow and the stalling point are determined accurately. However, calculations predict a jump-like transition to flow separation approximately in the middle of the smooth transition section as per experimental measurements. Also, calculations somewhat overestimate the force acting on blade section under separated flow conditions, which can be explained by introduced simplifications.

Based on the comparison of predictions and experiments one can conclude that the method developed for predicting the lifting force and drag of blade sections at arbitrary incidence angle has good accuracy. Therefore, this method will be further used for calculation of flow around propeller blades.

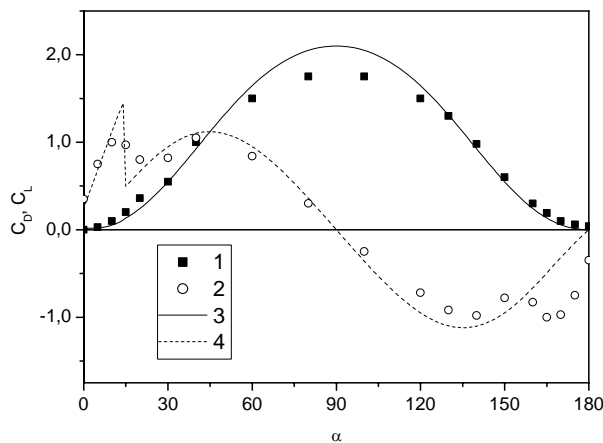


Fig. 3. Analytical and experimental relations of lifting force and drag coefficients of blade section No.7 (Miniovich 1958).

Experiment: 1 – C_D , 2 – C_L , calculations: 3 – C_D , 4 – C_L .

3 CALCULATION OF FORCES ON PROPELLER

A method based on propeller strip theory was developed for calculation of forces acting on the propeller in a strongly oblique flow. This method is a modification (Bushkovsky & Yakovlev 1998) of a well-known Pappel method (Basin & Miniovich 1963).

According to the developed method the hydrodynamic forces producing the propeller thrust and torque are determined for cylinder blade sections. The magnitude of these forces depends on the blade section incidence and flow velocity past blade section. W_i (Fig. 2). The velocity W_i , in its turn, is governed by the velocity of flow incident on propeller blade and propeller-induced velocities. The radial component velocity is ignored. The

axial and tangential velocity components of oblique flow incident on the propeller blade is represented as follows

$$\begin{aligned} V_x &= -V \cdot \cos\psi \\ V_\theta &= -\Omega r - V \sin\psi \cdot \sin\left(\Omega t + \frac{2\pi}{Z}j + \theta\right) \end{aligned} \quad (7)$$

where $j = 0, 1, \dots, Z - 1$; V - incident flow velocity (Fig. 1), Ω - propeller speed of rotation, Z - propeller blade number, t - time, ψ - flow angle.

The calculations have revealed that it is possible to ignore chordwise variations of incident flow velocity and assume that $\theta = \theta_0(\vec{r})$, where θ_0 - angular coordinate of mid-chord (Fig. 2).

For finding the blade section incidence angle one has to know the propeller-induced velocities for the given cylinder section. The velocities induced in usual operating propeller modes and in case of reverse jet are determined in accordance with the basic version of the method (Bushkovsky & Yakovlev 1998). In this case it is assumed that a jet keeps its cylinder form while the step of vortex sheets depends on operating mode. This assumption is valid for all modes with exception of reverse jet mode when the incident flow velocity and propeller-induced velocities have the same order of magnitude but opposite directions. A special coefficient is introduced for modeling the flow of reverse-jet type taking into account the finite length of the vortex sheet. This coefficient depends on the jet length determined as per (Rusetsky & Prischemihina 1981). This simplified model is acceptable because the duration of propeller operation during ship maneuver is usually limited. For the case of transition to separated flow pattern around blade the induced velocities are calculated based on estimated circulation.

The propeller induced velocity w depends on velocity circulation around the blade and, therefore, on the effective incidence angle of blade section α . However, the effective incidence angle depends, in its turn, on induced velocities. Thus, the value of this angle can be obtained by solving the following equation resulting from the velocity triangle (Fig. 2).

$$\text{ctg}(\varphi - \alpha) = \frac{V_\theta - w_\tau(\alpha)}{V_x + w_x(\alpha)} \quad (8)$$

where φ - pitch angle of blade section, w_x , w_θ - propeller-induced velocity components.

This is a non-linear algebraic equation with respect to unknown α . It is solved by successive approximation method.

For obtaining the force and moment on propeller it is required to solve equation (8) for a set of blade cylinder sections and find C_L and C_D by the method described in Section 3, and then integrate the obtained forces with respect to the radius.

It should be noted that an oblique flow angle causes changes in the relationship between velocity and blade

angle (7), as a result the forces will undergo periodic changes. For obtaining steady force components it is required to calculate forces for each angle of blade rotation and only after that to average these forces with respect to the variable $\tau = \Omega t$ within the interval from zero to 2π . As a result of this averaging by summing forces on individual blades we obtain final equations for open water propeller thrust and torque coefficients in oblique flow.

$$K_{TX0} = \frac{ZJ^2}{4\pi} \int_{r_0}^1 \int_0^{2\pi} \overline{CW}_i^2 [C_Y \cos\beta_i - C_X \sin\beta_i] d\tau d\bar{r} \quad (9)$$

$$K_{Q0} = \frac{ZJ^2}{8\pi} \int_{r_0}^1 \int_0^{2\pi} \overline{CW}_i^2 r [C_Y \sin\beta_i + C_X \cos\beta_i] d\tau d\bar{r}$$

where r_0 – hub radius, $\beta_i = \varphi - \alpha$.

Similarly, transverse components of forces and moments are calculated.

The efficiency of the developed method has been proved by comparison of analytical results with experimental data from (Binek & Muller 1975). This reference gives component forces and moments obtained in propeller tests for a range of advance ratios varied from zero to unity at fixed flow angles from 0° to 360° (at a 15° step). A four-bladed Wageningen B-series propeller is considered with the blade area ratio of $A_E/A_O = 0.7$.

Below are given comparisons of analytical and experimental data for longitudinal and transverse forces on propeller in the flow-fixed coordinate axes (1) as well as the moment at propeller axis. The transverse component force on propeller along Oy – axis, K_{TY} , is absent when the flow angle is within the propeller rotation plane.

It is seen from the comparison that the agreement with test data is satisfactory both for small (Fig. 4) and large (Fig. 5) advance ratios.

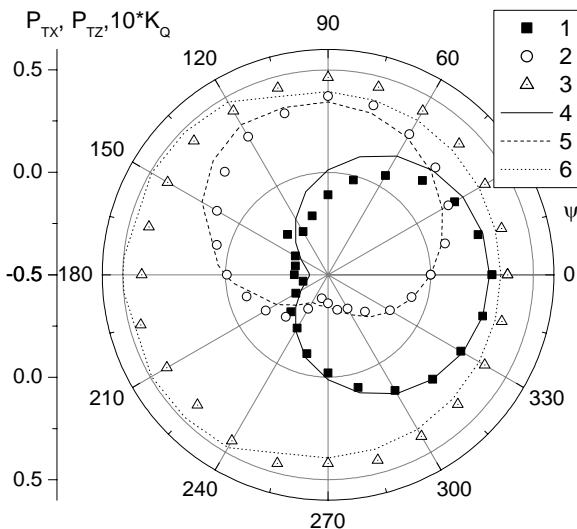


Fig. 4. Comparison of analytical and experimental relationships of component propeller forces and moments versus flow angle ψ ($J=0.2$). Experiment: 1 – P_{TX} , 2 – P_{TY} , 3 – K_Q , calculations: 4 – P_{TX} , 5 – P_{TY} , 6 – K_Q .

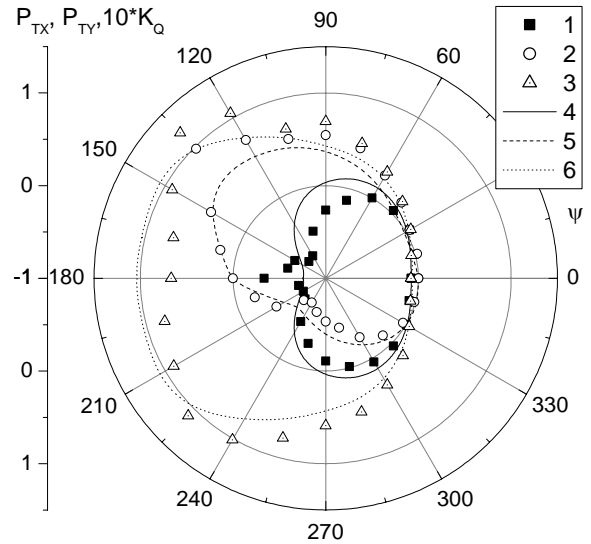


Fig. 4. Comparison of analytical and experimental relationships of component propeller forces and moments versus flow angle ψ ($J=1.0$). Experiment: 1 – P_{TX} , 2 – P_{TY} , 3 – K_Q , calculations: 4 – P_{TX} , 5 – P_{TY} , 6 – K_Q .

4 CALCULATION OF FORCES ON PROPULSION POD WITHOUT PROPELLER

The forces on pod without propeller can be calculated using the general principles described in Section 3. The forces on pod at small steering angles under separation-free flow conditions can be estimated by the boundary element method with corrections for viscosity (Yakovlev 2008). However, since the range of such angles is limited, it is more interesting to estimate forces on pod under separated flow conditions. In this case the forces are calculated using the above-described method based on the Rayleigh formula.

The calculations have proved that formula (5) can be used to model the main force components, but deviation of experimental data from the analytical curve is dependent on the Reynolds number. Thus, in addition to expression (6) for C_0 and relation $\sigma(\alpha)$ the formulas for force estimation should include Reynolds number function. Let us introduce it in the following way

$$C_{DP} = \kappa \cdot C_N(\psi) \cdot \sin\psi + A(\psi, Re)$$

$$C_{LP} = \kappa \cdot C_N(\psi) \cdot \sin\psi + C_{L0} \cdot \sin\psi \quad (10)$$

where coefficient C_N is determined according to (5), A – accounts for the Reynolds number function for laminar or turbulent flow conditions, C_{L0} – correction for side force due to longitudinal pod asymmetry, coefficient κ accounts for three-dimensional character of separated flow pattern

$$Re = \frac{V\sqrt{\Sigma}}{\nu}, \Sigma - \text{wetted surface of pod.}$$

In this case all force coefficients are obtained by reference of respective values to $\rho \frac{V^2}{2} \Sigma$.

Expressions (10) include a number of characteristics that can be found only by estimations. These include: dependence of A on angle of rotation in laminar, turbulent and transient flow conditions, correction C_{L90} and pressure in stagnant zone σ in formula (6). These characteristics were estimated using the results of pod model test data processing.

Fig. 6 presents the calculation of force coefficient C_{DP} and C_{LP} for other pod and corresponding experimental data. It is seen that the estimates are in good agreement with the experiment.

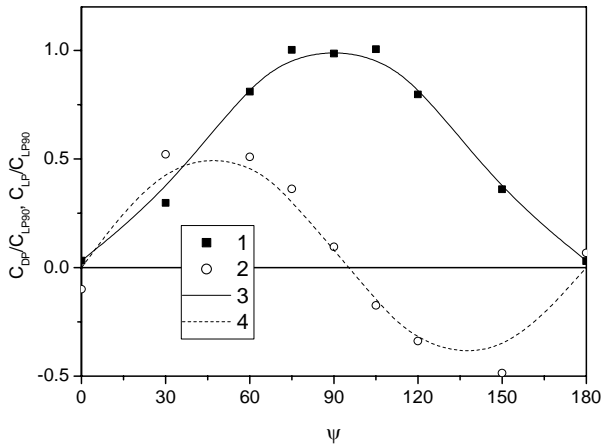


Fig. 6. Coefficients of longitudinal and transverse forces on pod without propeller. Coefficients are normalized by experimental values of C_{LP} at $\psi=90^\circ$. Experiment: 1 – C_{DP} , 2 – C_{LP} , calculations: 3 – C_{DP} , 4 – C_{LP} .

5 CALCULATION ON FORCES ON PROPULSION POD

Propeller and hull interaction is traditionally modeled by wake factor w and thrust deduction coefficient t . Let us assume that interaction of propeller and pod can be modeled using a similar method. The difference is that both coefficients will be dependent not only on the advance ratio but also on the pod steering angle.

$$w = w(J, \psi)$$

$$t = t(J, \psi)$$

Experimental data for a number of propulsor models were used to obtain these relations. Forces and moments were calculated for subject propellers. The coefficients w and t were determined so that experimental values could be obtained for pod and pod-integrated propeller using calculated data.

Based on the obtained relations for t and w one can calculate the pod characteristics. Since it is implied that the mutual influence of pod and propeller is weakly depend on the propeller and pod geometry details, the calculations would be most accurate of propulsion pods of similar type.

The forces on pod are calculated as follows. First, the forces and moments of open-water propeller are calculated (method of Section 3) and pod characteristics without propeller are estimated (method of Section 4). Then, using wake factor w the open-water propeller

curves (9) are extrapolated to the case when the propeller is operating as part of the propulsion pod.

$$K_{TX} = K_{TX0}(J \cdot (1 - w), \psi)$$

$$K_Q = K_{Q0}(J \cdot (1 - w), \psi)$$
(11)

Then, calculations are performed for the integrated propulsor taking into account the coefficients w and t .

Fig.7 provides an example of calculation of longitudinal force P_{SX} on pod and its comparison with experimental data for two advance ratios. The calculations were performed in accordance with the above-describe method, while the experimental data were obtained in the model tests at the Krylov Shipbuilding Research Institute. The comparison demonstrates good accuracy of the developed method for the propeller operating modes under consideration.

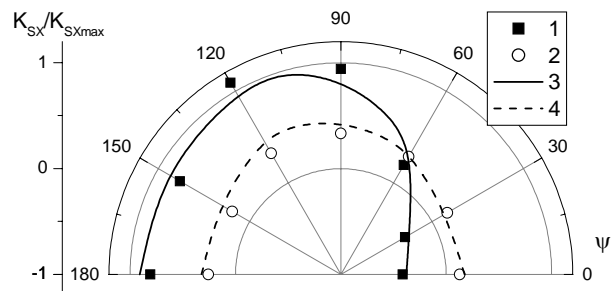


Fig. 7. Analytical and experimental relations of longitudinal force on pod at different advance ratio J normalized by maximal values. Calculations: 1 – $J=1.3$, 2 – $J=0.5$, experiment: 3 – $J=1.3$, 4 – $J=0.5$.

6 CONCLUSION

The calculation method presented in the paper is able to predict with good accuracy the forces arising on propulsion pod and propeller in off-design operating conditions including 0 to 360 degrees pod steering angles and a wide range of advance ratios.

Good accuracy of estimations is ensured by a combination of analytical methods including empirical relations obtained from model experiments. The reliability of analytical estimates has been confirmed by stepwise testing of all the above-described methods.

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