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PREDICTION OF THE SCALE EFFECT FOR THE HULL-PROPELLER INTERACTION FACTORS

DMITRY V. BAGAEV, MICHAIL P. LOBACHEV, NIKOLAI A. OVCHINNIKOV, ANDREY E. TARANOV

Krylov State Research Centre (KSRC)
44, Moskovskoe Shosse, St.Petersburg, 196158, Russia
e-mail: krylov@krylov.spb.ru

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Abstract The paper is focused on the possibility of scale effect calculations using unsteady solution of the Reynolds equations (URANS method) for arbitrary hull shapes. URANS method is used for simulation of a flow around the tanker 12990 with rotating propeller in both model and full scales. The computational results have been verified against the model and full scales experimental data for the drag, thrust and moment. The scaling of the wake factor is done using 4 different semi-empirical approaches.

Effects of the surface roughness of the hull and propeller on the propulsion characteristics are considered. Some advantages and disadvantages of the presented method are discussed in the paper.

1. INTRODUCTION

Nowadays prediction of the ship propulsion characteristics in design practice is usually based on the experiments (towing tank, wind tunnel and so on). During model tests we have to neglect some similarity relations, i.e. the model tests are performed with partial similarity modeling. Therefore the problem of appropriate scaling from the model to the full scale is very important. Huge amount of investigations in the towing tanks have been done world-wide, but still the modern methods of scaling are imperfect. Variety of different existing approaches confirms it very well. That situation was stated in the final report [1] of 23rd ITTC although the recommended scaling procedure exists (ITTC QM Procedure 4.9-03-03-01.2).

The ITTC-78 procedure was recommended for the using in the speed prediction of the single-screw transport vessels [2]. Considering the significance of this procedure which takes into account all components of the ship propulsion characteristics, it is necessary to point out that ITTC-78 procedure in its essence is a mix from outer (estimation of the characteristics depending on the non-modeled similarity criterions) and inner (examination of the methodological uncertainty) problems [3]. This is connected with the fact that not all regulations of the ITTC-78 are well-grounded physically. Some basic regulations of ITTC-78 were criticized in [4].

In consequence of insufficient foundation of the ITTC-78 procedure and limitation of its applicability (single-screw transport vessels) the development of the new methods of scaling from the model test to the full scale is in progress up to now. The present work is focused on the method of the scale effects calculations using unsteady solution of the Reynolds equations (URANS method) for the ship hull equipped with propeller. Due to the complexity of such calculation and high performance computer requirements, this type of scaling methods starts to be propagated recently. Additionally to use computational fluid dynamic (CFD) for scaling methods effectively it is necessary to develop special procedure to speed up the pre-processor setup and mesh generation and therefore to reduce the overall computational time. Previously applied computer methods [5, 6] use a combination of URANS approaching and semi-empirical relations.

At present the existed URANS-based computational methods do not allow to predict ship propellers characteristics with the accuracy corresponding to the experiment. However one can suppose that discrepancies are caused by poor resolving of the tip vortices shedding from the ship propeller. This fact has effect on the estimation of the pressure distribution so the same errors should take place both for the model and the full scales. Therefore it is possible to use successfully the URANS-based methods for prediction of the scale effects.

2. NUMERICAL SETUP

The calculation of interaction factors using unsteady solution of the Reynolds equations was performed for the tanker hull 12990. Main dimensions of the hull 12990 and its model 11409 manufactured in scale 32.5 are listed in the Table 1. All calculations were performed for the design loaded condition.

Table 1: Main dimensions of the hull 12290 and model 11409

Main dimensions	model	full scale
Length on waterline, L_{WL} m	7.231	235.0
Breadth, B m	0.994	32.3
Draught, T m	0.3815	12.4
Displacement, V m^3	2.167	74400
Wetted surface area, Ω m^2	10.777	11383

Propeller model 7849 was chosen for the numerical study and has the following parameters: number of blades, n = 4, diameter, D = 200 mm, pitch ratio P/D = 0.658, blade area ratio $A_E/A_0 = 0.713$, skew angle 0°. The specific feature of the propeller 7849 is increasing of the pitch angle from the hub to the blade tip. Although it does not comply with the modern design practice, which recommends reducing pitch angle in the tip area to decrease vibration, two tankers (“Pobeda” and “Marshal Vasilevsky”) were equipped with the propeller 7849 and comprehensive tensometric propeller data were recorded during the sea trials.

For simulation of the flow around the hull including the rotating propeller the CFD (computational fluid dynamics) software Star-CCM+ version 7.0 was used. Reynolds equation for the incompressible flow is solved using the nonlinear k-ε turbulence model in the high Reynolds number formulation.

Rotation of the propeller is simulated using the “sliding grid” interface. The computational grid is divided into two regions. The cylindrical region is formed around the propeller. The external surface of the region forms the sliding interface between the rotating region (propeller) and the fixed region (hull). The rotating region completely covers the propeller and neither intersects nor touches the hull. There should be a sufficient gap between the hull and rotating region to generate the proper grid between the propeller and interface surface as well as between the interface surface and the hull surface. The flow inside the cylindrical region is solved in rotating coordinate system.

The main aims of the work are interaction factors between hull and propulsor, therefore the free surface effects were not considered. For the conventional displacement ships the influence of the free surface effects on the interaction factors is rather weak [7]. In numerical setup the symmetry boundary condition was used on the design waterline.

To estimate the interaction factors between the hull and propulsor the set of numerical simulations was done in accordance with experimental procedure [7]. To reduce the computational time the constant velocity mode was chosen as preferable.

The estimation of the interaction factors is performed in 4 steps:

Step 1. The flow around the hull without the propeller is simulated.

Step 2. The flow around the propeller in open water condition is simulated for different inflow velocities. As opposed to experiments the flow is considered to be turbulent a priory and there is no need to provide some kind of turbulization.

Step 3. The flow around the hull with rotating propeller is simulated for the different rotational speeds and fixed towing speed. The data for the hull resistance, propeller thrust and torque depending on the advance ratio are obtained.

Step 4. The interaction factors are estimated using the appropriate procedure [7] and previously obtained data.

The calculations were performed for the extend Reynolds number range, starting from the corresponding to the model experiment and ending with the corresponding to the sea trials. The operational points for the model and full scale are presented in the Table 2. The Reynolds numbers for the ship hull and propeller are defined as following:

$$Rn = \frac{VL_{WL}}{\nu}, \quad Rn_p = 5\frac{nD^2}{\nu}\frac{A_E}{A_0}\frac{1}{z}, \tag{1}$$

where V is the vessel speed, L is the hull length on waterline, D is the diameter of the propeller, n is the rotational speed, A_E is the expanded blade area, A_0 is the propeller disc area, z is the number of blades. The advanced ratio J corresponding to the operational point is equal to 0.6087.

Table 2: Operational points

Condition	Rn	Rn_p
Model scale	$8{,}872 \cdot 10^6$	$3{,}593 \cdot 10^5$
	$1{,}000 \cdot 10^8$	$4{,}050 \cdot 10^6$
Full scale	$1{,}632 \cdot 10^9$	$6{,}611 \cdot 10^7$

3. RESULTS

3.1 Viscous resistance.

The comparison between the numerical solution and approximation according to Prohaska [8] for the viscous resistance of the tanker 12990 is presented on the Fig.1. Estimation of the form-factor using Prohaska method was performed on the basis of multiple measurements for the small Froude numbers. This approach allows us to reduce inaccuracy of form-factor estimation significantly. Two different extrapolation curves were used in Prohaska method for the friction resistance of the flat plate: ITTC-57 curve and curve of Pustoshny-Kotlovich. Dependence of the friction resistance on the Reynolds number is described as follows:

$$C_{Fo} = \frac{0.075}{(\lg Rn - 2)^2} \qquad \text{ITTC-57 curve;}$$

$$C_{Fo} = \frac{0.323}{(\lg Rn)^{2.45}} \qquad \text{curve of Pustoshny-Kotlovitch.}$$

For the Reynolds number $Rn=1.521\cdot 10^9$ the difference between the results obtained in the numerical simulation and the results of the Prohaska method achieves 1.6% for the curve of Pustoshny-Kotlovitch and 9.5% for the ITTC-57 curve.

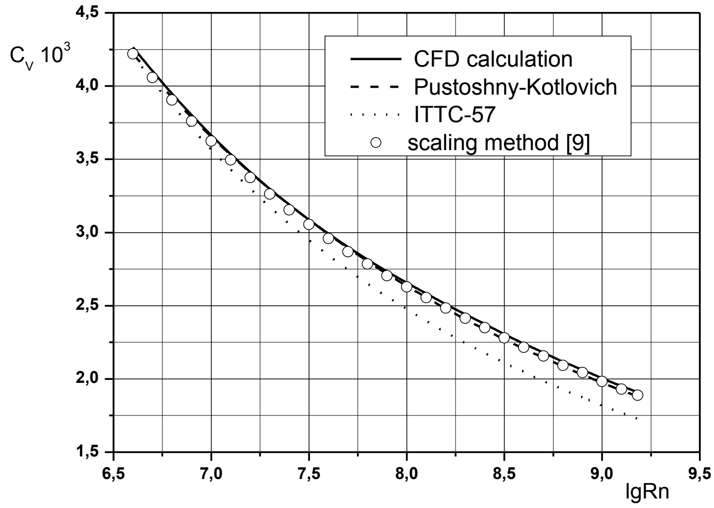

Figure 1: Tanker 12990. Viscous resistance for the different Reynolds number

The fact that curve of Pustoshny-Kotlovitch provides the results which are very similar to the URANS solution has a simple explanation. The curve of Pustoshny-Kotlovitch was derived with assumption that logarithmic velocity profile exists inside the boundary layer of the flat plate. This assumption complies with the logarithmic wall function in the URANS solution and based on the numerous measurements of the velocity profile inside the boundary layer. The ITTC-57 curve is a simple extrapolation curve, which was chosen on the basis of the best agreement between the scaled experimental data and the sea trials data. The ITTC-57 curve differs substantially from the relations based on the semi-empirical theory of the boundary layer. The curve of Pustoshny-Kotlovitch seems to be more physically grounded. Additionally the URANS based scaling method proposed by Pustoshny et al.[9] plotted on the Fig.8. The results of procedure [9] are very close to CFD calculation and Pustoshny-Kotlovich curve.

3.2 Performance curves of the marine propeller in open water

The comparison between the numerical solution and the experimental data for the thrust coefficient $K_T(J)$ of the marine propeller 7849 at different advance ratios J is plotted on the Figure 2a. Figure 2b represents the same dependency for the moment coefficient $K_Q(J)$ values. Both numerical and experimental investigations were completed in open water conditions for the model Reynolds numbers. There are some discrepancies between experiment and URANS solution. The value of the thrust coefficient is slightly lower than obtained experimentally; while the moment coefficient values are slightly higher. It should be noted that numerical solution for the modern ship propellers with unloading on the blade tip provides usually more accurate results. Apparently the disagreement between experimental tests and calculations for the marine propeller 7849 can be explained by insufficient resolution of the tip vortices which are quite strong due to increased pitch at the blade tip. Nevertheless the influence of the scale effect on the performance curves completely corresponds to the modern conception. In opposition to the ITTC-78 procedure one can state the scale effect of the thrust coefficient takes place as well as the scale effect of the moment coefficient. Moreover the scale effect of the thrust coefficient depends on the advance ratio. It is obviously connected with the repositioning of the critical point on the leading edge.

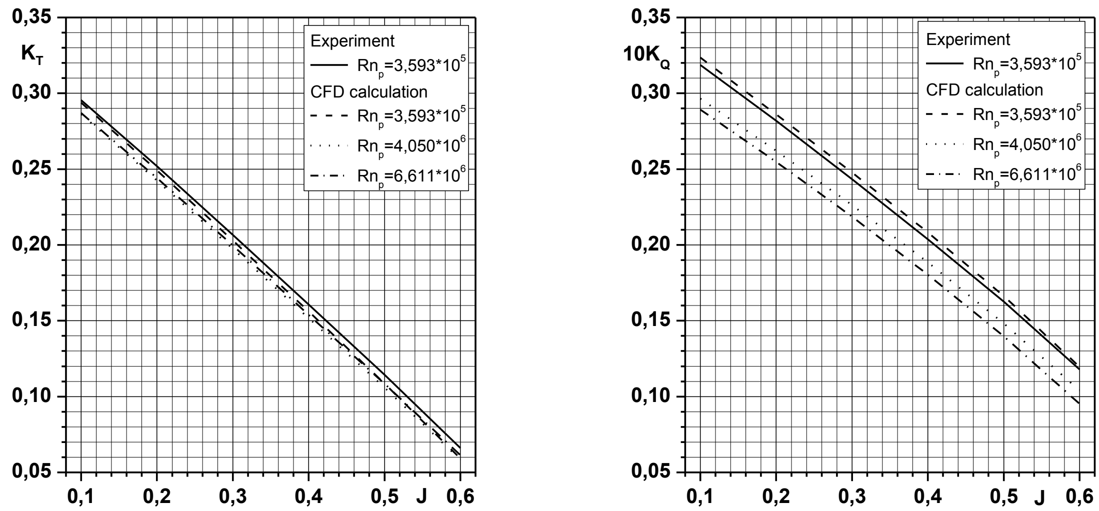

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Figure 2: Marine propeller 7849. Performance curves; open water condition

The comparison between the numerical solution and the experimental data for the propeller efficiency η_0 for the marine propeller 7849 at different advance ratios J is plotted on the Figure 3a. Although the propeller efficiency in calculations is lower than in experimental data, the shape of the curve seems to be very similar to the experimental one. That allows us to use the numerical results for the estimation of the scale effect. Dependencies of the propeller efficiency on advance ratio are showed on the Figure 3b. As a basis for the comparison the propeller efficiency corresponding to the model Reynolds number was taken:

$$d\eta_0 = (\eta_{0Rn} - \eta_{0Rnm}) \cdot 100\%, \tag{2}$$

where Rn denotes an arbitrary Reynolds number, Rnm denotes a model Reynolds number. One can estimate the advance ratio J, which takes the full scale wake factor into account:

$$J = 0.6087 * (1 - 0.361) = 0.389. \tag{3}$$

According the Figure 3b the variation of the propeller efficiency corresponding to this advance ratio is 6.37%, which is quite expectable.

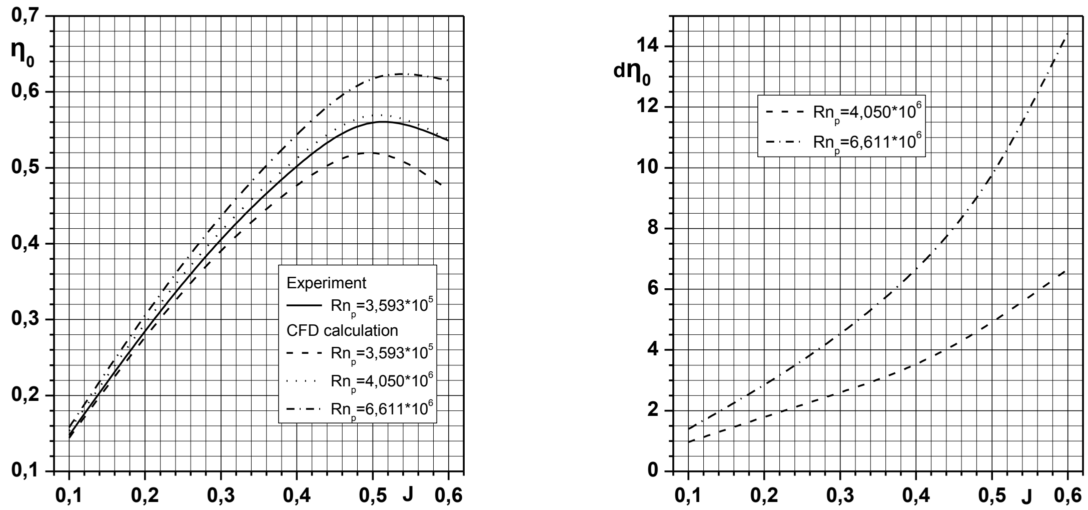

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Figure 3: Marine propeller 7849. Propeller efficiency for different Reynolds numbers; open water condition

3.3 Performance curves of the marine propeller operated behind the hull

The comparison between dependency of the coefficient $K_T(J)$ on the advance ratio obtained experimentally and calculated for the marine propeller 7849 operated behind the model hull 11409 is shown on the Figure 4. Moment coefficient for the same problem is plotted on the Figure 5. The experiment was conducted using standard ITTC procedure. Additionally the multiple (14 times) measurements for 4 different advance ratios were implemented. It allowed to estimate the random errors as well as to increase the measurement accuracy using the statistical analysis.

The quality of the results remains close to the previous paragraph - the thrust coefficient is slightly lower than in experimental data. Insufficient resolution of the tip vortices results in similar errors in the process of the numerical simulation of the marine propeller in open water condition as well as behind the hull. This similarity allows us to expect the wake factor values to be correct.

During the sea trials of the tankers “Pobeda” and “Marshal Vasilevsky” the tensiometric measurements of the shaft moment were carried out. The moment coefficients obtained from those measurements are plotted on the Figure 5 as well. The numerically predicted moment coefficient is slightly lower than experimental one. The fact that propeller roughness was not considered in the URANS simulation can probably explain such discrepancies between the experiment and calculation. Since the used CFD software supports modeling of the roughness, this fact has been proved through additional calculations with rough propeller. As the average size of the propeller roughness the values of 7 and 10 µm were taken. This range of roughness corresponds to the cathode deposits. Figure 6 presents the comparison between the sea trial data and calculated moment coefficient for smooth and rough propeller. Taking into account the roughness on the propeller allows achieving better agreement between the CFD calculations and sea trials data.

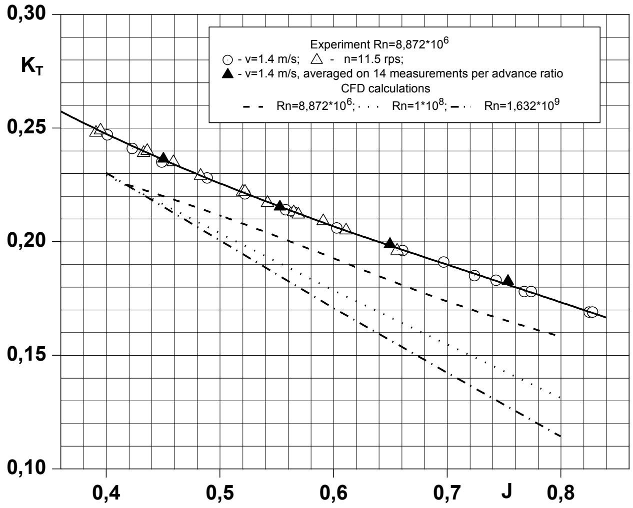

Figure 4: Thrust coefficients of the marine propeller 7849 operated behind the model 11409

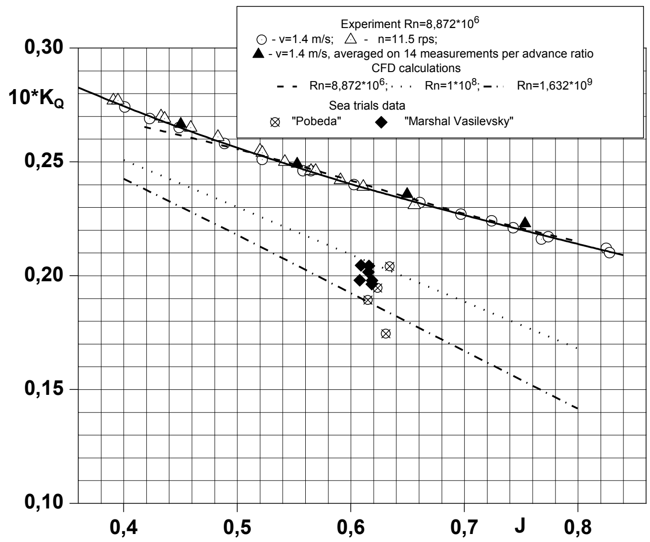

Figure 5: Moment coefficients of the marine propeller 7849 operated behind the model 11409

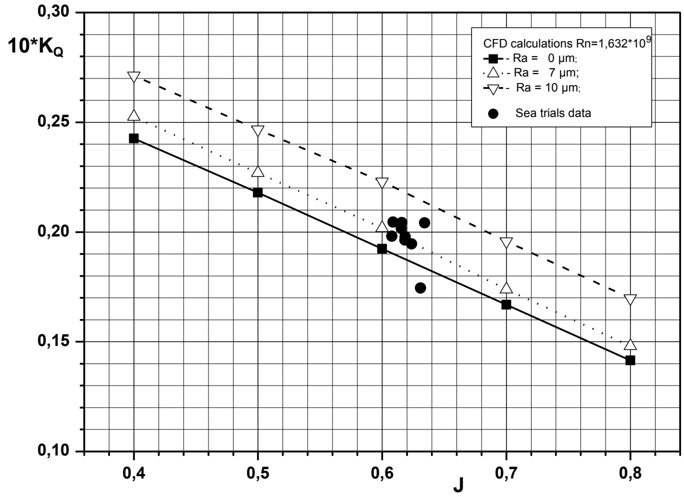

Figure 6: Moment coefficients of the marine propeller 7849 operated behind the model 11409. Influence of roughness

3.4 Interaction factors

Figure 7 helps us to understand the accuracy of the presented method. Numerically estimated interaction factors are plotted on the Figure 6 in comparison with experimental data. The calculations were conducted for the model scale. The agreement is not comprehensive, but seems to be rather good. Underestimation of the propeller thrust in open water conditions is close to the losses of thrust behind the hull, therefore the predicted wake fraction W is sufficiently accurate. That can be clearly recognized from the Figure 7.

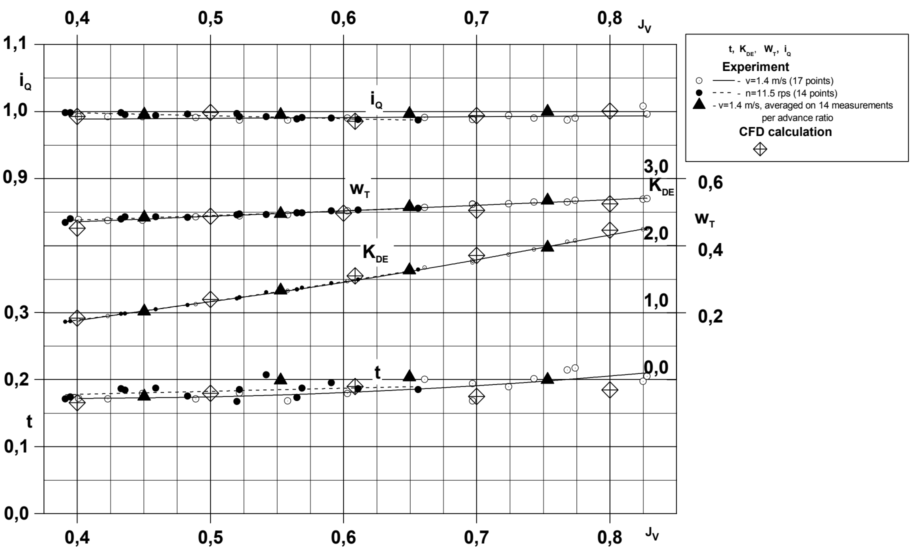

Figure 7: Interaction factors of the marine propeller 7849 and the model hull 11409

Analyzing the interaction factors computed for the wide range of Reynolds number, starting from corresponding to the model experiment and ending with corresponding to the sea trials, one can state that scale factor has very weak impact on the thrust deduction factor t and relative rotative efficiency i_Q. This fact fully corresponds to the ITTC assumptions. Of course, there are some deviations for different Reynolds numbers, but they are within the measurement uncertainty for the model scale. Therefore the results for the thrust deduction factor and relative rotative ratio are not in the scope of the present work.

Numerical and experimental data for the wake factor W_T are plotted on the Figure 8. The model measurements were conducted in pure water and in polymer solution. The wake factors defined on the basis of the sea trials using different statistical analysis and results of the scaling using 4 different methods are presented on the Figure 8 as well. The methods of the scaling are defined as following:

Method 1. This procedure is based on the combination of the URANS calculation of the ship hull without propeller and semi-empirical assumptions, which allow defining the wake factor W_T using the nominal wake factor W_N. This is a modification of the Pustoshny-Titov method performed in Krylov Shipbuilding Research Institute [4,12]. According to this method the following relation between wake factor W_T and nominal wake factor W_N is used:

$$W_T = \frac{W_N \cdot \sqrt{2}}{\sqrt{1+\sqrt{1+C_{TA}}}}. \tag{4}$$

Herein the main features of the flow around the hull will be taken into account through the nominal wake factor only.

Thrust loading coefficient C_{TA} can be calculated using the effective thrust loading coefficient K_{DE} as follows:

$$C_{TA} = \frac{8}{\pi} \cdot \frac{1}{1-t} \cdot \frac{1}{(1-W_T)^2} \cdot \frac{1}{(K_{DE})^2}, \; K_{DE} = DV \cdot \sqrt{\rho / T_E}\,. \tag{5}$$

Finally the nonlinear equation for wake factor W_T will be solved iteratively. Wake factor for the full scale ship can be obtained in following way:

$$W_{TS} = W_{TM} + (W_{TS}^{calc} - W_{TM}^{calc}), \tag{6}$$

where index *calc* denotes the calculated quantities, index *S* - full scale, index *M* – model scale.

Method 2. This method was proposed by Kanevsky [14]. It is based on the investigation of the hull roughness and its influence on the hull-propeller interaction [13]. Kanevsky offered an approximation for the wake factors depending on the viscous resistance ratio:

$$\frac{W_{TS}}{W_{TM}} = 0.4 + 0.6 \cdot \frac{C_{VS}}{C_{VM}}, \tag{7}$$

which has been successfully used in Krylov Shipbuilding Research Institute for the speed prediction. C_{VS} is the viscous resistance of the ship; C_{VM} is the viscous resistance of the model.

Method 3 - “Speed prediction method ITTC-78”. After extensive investigation through model-ship analysis, the following correlation formula for the wake fraction was adopted by ITTC-78 [2]:

$$W_{TS} = (t + 0.04) + (W_{TM} - t - 0.04) \cdot \frac{(1+k) \cdot C_{FoS} + \Delta C_F}{(1+k) \cdot C_{FoM}}. \tag{8}$$

Equation (8) is based on the assumption that viscous part of the wake fraction depends linearly on the viscous coefficient C_V. C_{F0} is the friction coefficient of the flat plate according to the ITTC-57; t is the thrust deduction factor; ΔC_F is the roughness correction.

Method 4. Denisov and Tumashek have proposed the following approximation based on the results obtained in [13]:

$$\frac{W_{TS}}{W_{TM}} = 1.5 \cdot \frac{C_{VS}}{C_{VM}} - 0.5 \cdot \left(\frac{C_{VS}}{C_{VM}} \right)^2 \tag{9}$$

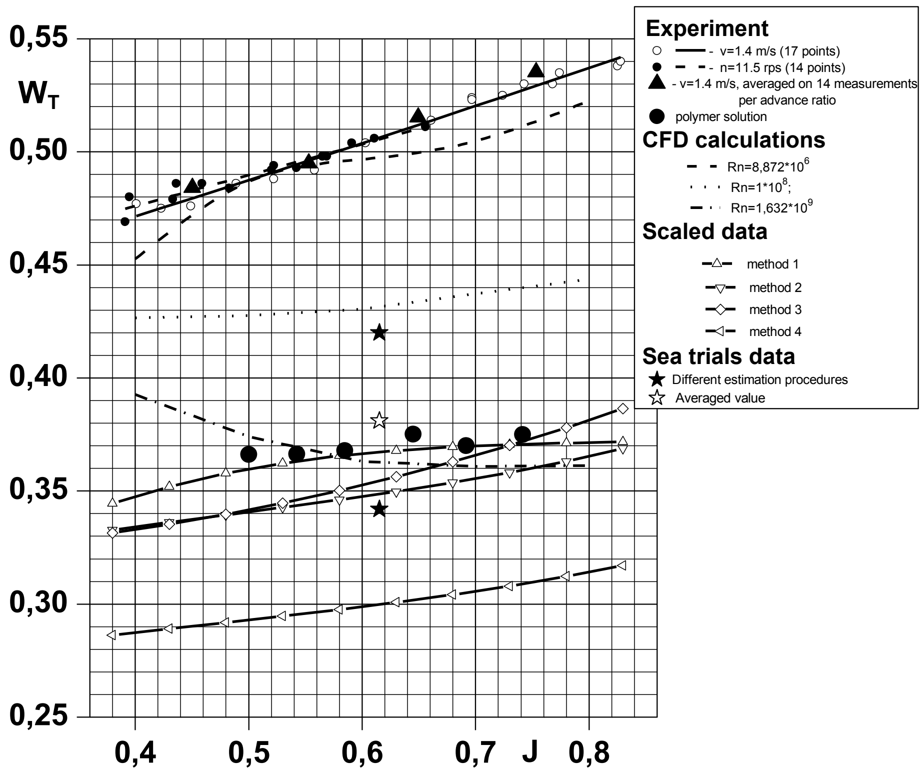

Figure 8: Wake factors W_T for model and full scales. Different approximation procedures

As it can be seen from Figure 8 all described methods except method 4 estimate the wake factor at the operational point J=0.6078 with acceptable quality. It must be admitted that lower values of the wake factor seem to be more plausible including the minimal value of W_{TS}=0.342. The results obtained by Orlov in polymer solution [15] confirm this suggestion. Wake factor obtained in polymer solution at operational point is about 0.37. Considering the increased resistance coefficient obtained in polymer solution, one can suggest that wake factor of 0.37 is rather overestimated. Thus, it is more likely that the wake factor at operational point lies between 0.342 and 0.37. It can be proposed to repeat the statistical analysis of sea trials data using the scale effect estimation obtained in the present work for the performance curves. The wake factor of 0.342 was obtained from the sea trials data using ITTC-78 procedure for the estimation of the performance curves.

The results almost all of used scaling procedures for the tanker 12990 are very close to each other. It should be noted that measured and simulated flow around this hull is rather conventional, without any specific features. It was reported in the work [6] that speed prediction for this kind of hull shapes can be done with high accuracy using the most of numerical methods. The same paper demonstrated that for the hulls with separation of the flow only the URANS-based method [5] allowed obtaining results agreed with sea trials data. While the method [5] is applicable for single-screw ships only, the URANS-method used in the present work allows us to simulate the flow around an arbitrary hull shape.

4 CONCLUSIONS

URANS-based method for the simulation of the viscous flow around the ship hull is applied to the 12990 tanker equipped with rotating propeller 7849 in both model and full scales. The results of the present study demonstrate that prediction of the scaling effect of the resistance, performance curves of the marine propeller (operated in open water condition as well as in the ship wake) and interaction factors can be performed in the same way without any additional empirical assumptions, except the embedded in URANS method (e.g. turbulence or roughness models). That allows us to conduct the calculation of the scaling effect for the arbitrary hull shape provided that the applicability of URANS method has been validated for this hull shape in the model scale. It should be noted that comprehensive experience in CFD accumulated in Krylov State Research Centre indicates that URANS methods are quite universal.

The significant requirements in computational time on the high performance computer can be considered as drawback of the presented method. The study of the scaling effect including numerical calculations for the 5 advance ratios in the model and full scales can be done on the cluster with performance of 1 TFlop in 2-3 weeks. Such requirements can be compensated by the fact that URANS calculations provide a lot of additional information concerning the local and integral flow characteristics. For example the pressure distribution on the propeller blades at any point of time can be obtained and consequently the estimation of the cavitation margin for the full scale can be done. Other time-averaged and instantaneous flow characteristics can be obtained as well.

The further development of the presented method can be done for better prediction of the propeller thrust and detailed analysis of the roughness effects.

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