An advanced Scaling Procedure for Marine Propellers

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ABSTRACT

In times of increased fuel oil prices the focus within the ship design process is highly on efficiency. Especially the vessel's propulsion is a key factor in optimising the fuel oil consumption. Therefore any amount of increase of the efficiency wants to be recognised and evaluated. Ship owner more and more postpone their decision about the propeller supplier after comparative model tests with two or more different propeller designs. But as the performance of propulsion is affected by scale effects these comparisons always offer room for discussions about the right way to apply such scaling calculations. Especially propeller designs with blade shapes that differ from the "conventional" type often enforce these discussions. Therefore the idea of the European project "PREFUL" was to investigate the possibilities of improvements of the scaling calculation in order to consider the differences between blade shapes more precisely. As a result the differences between the several scaling procedures are shown, especially in comparison to the results of the new "stripe method", which was developed within the project. The project was funded by the German Ministry of Economics.

Keywords

Scale Effects, RANSE, ITTC'78, Lerbs/Meyne, Open Water Efficiency

1 INTRODUCTION

Model tests are still a very important instance within the ship design process. The advantages are that the tests were carried out by a neutral instance and ship designer or supplier and the prospective ship owner can discuss about the results based on agreed measurements. Besides the question of costs the most important disadvantage of model tests is the model scale itself. Especially for the propeller the achievable Reynolds numbers are far away from the expected once for full scale. Therefore correction procedures for the scale effects were introduced in the model testing procedure many years ago. But the methods are concentrated on one (more or less) representative blade section. And as the open water test is still a basic element of the propulsion test procedure this paper is addresses to the correlation between the measurements of the behaviour in the open water model test and the predictions of the propeller behaviour under full scale conditions. Behaviour in that case means the relationship between given thrust T_O and required torque Q_O in the open water depending on the inflow conditions. That means the efficiency of the propeller depending on the advance coefficient J.

In order to improve the predictions of these full scale conditions cavitation tunnel tests as well as viscous calculations were introduced. Furthermore a stripe method was developed for scaling calculations considering the whole blade characteristic. The idea is to come to more sensitive scaling procedures that may not disadvantage to modern or unconventional propeller designs.

2 JUSTIFICATION OF OPEN WATER TESTS

The first question may be: Why do we need an open water test with all related scaling problems if there cannot be a real validation with full scale, because there is no economical reasonable way of carrying out a full scale open water test.

But there are several reasons to keep the open water test within the process chain of the propulsion test. First of all there is a clear advantage of breaking down the propulsion test into scalable and non-scalable terms. But this also needs knowledge of the open water performance of the tested propeller. And even the task of comparing to propeller designs can be carried out very easy and without additional influence by comparing the open water behaviour.

But the main reason for carrying out open water tests is the fact that we can separate the frictional effects from the propeller performance. In case of open water tests there is no need to keep the Froude-similarity. Thus the tests can be run at higher Reynolds numbers and therefore the differences between model scale and full scale, with other words the demand for corrections, can be reduced. In order to give an impression about the relations between model scale and full scale Figure 1 shows the achievable ranges of Reynolds numbers for open water tests in the tank as well as in the cavitation tunnel in comparison with typical Reynolds numbers in full scale.

For a detailed discussion some definitions have to be clarified. The Reynolds number Rn0.7 indicating the x-axis is based on the chord c0.7 of blade section at radial position $r0.7 = 0.7R$ (with R as the radius of the propeller) and the related undisturbed flow at the same section (rotational speed ω, the homogeneous inflow speed u and the dynamic viscosity ν).

$$Rn_{07} = c_{07}\frac{\sqrt{\omega^2 r_{07}^2 + u^2}}{\nu} \tag{1}$$

The graph shows the efficiency $\eta_O = \frac{u \cdot T_O}{(2\pi n Q_O)}$ of the propeller 2830 in the open water conditions for a give shaft

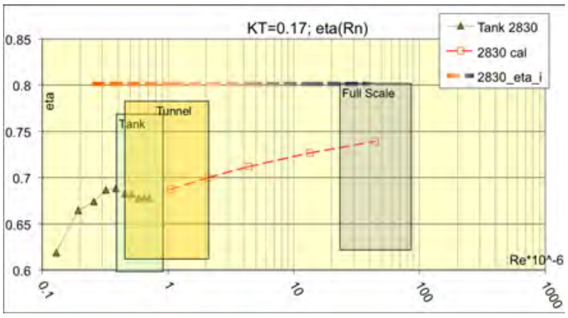

Figure 1: Open water efficiency depending on the Reynolds number

speed n based on measurements in the tank as well as the prediction of the efficiency for higher Reynolds numbers up to full scale. The prediction is done by taking the "inviscid" propeller efficiency in considering the values T_{in} and Q_{in} calculated with a panel method. All compared Reynolds depending propeller efficiencies are related to the same thrust coefficient $k_T = \frac{T_O}{(\varrho n^2 D^4)}$.

3 JUSTIFICATION OF OPEN WATER TESTS

In order to schieve higher Reynolds numbers for the open water tests the large conventional cavitation tunnel in HSVA with a cylindrical measuring section if 750mm in diameter was used (see Figure 2).

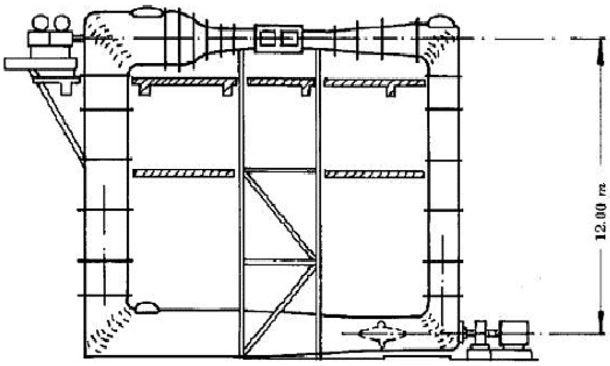

Figure 2: Large cavitation tunnel of HSVA

After an intensive review of the available stock propellers at HSVA some older propeller geometries from former tests as well as a more actual MMG geometry were chosen for the tests in the conventional tunnel. The MMG propeller e.g. comes with a model diameter of 260mm and is shown in Figure 3.

But as the model tests in the cavitation tunnels result in a higher Reynolds number there is the disadvantage of possible blocking of the tunnel flow due to the propeller geometry. In that case the assumption of undisturbed homogenous flow, as requested for an open water test, is violated. Therefore the tunnel tests need corrections. The advance coefficient $J = \frac{u_T}{(nD)}$, related to the tunnel speed u_T must be corrected to a $J' = \frac{u}{(nD)}$ based on the averaged or equivalent free field velocity u.

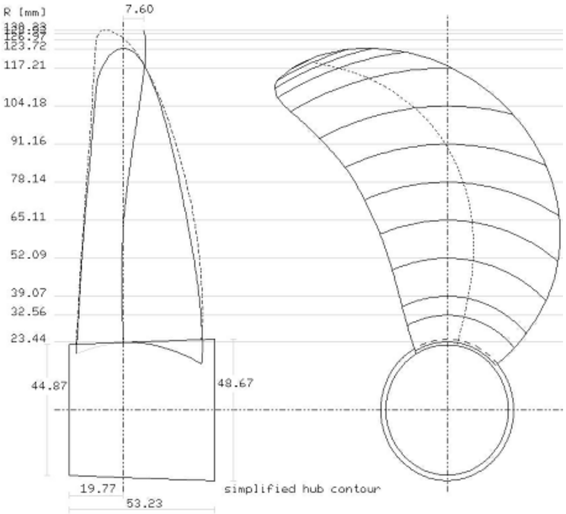

Figure 3: Geometry Propeller P2671

A well-known correction method was developed by Wood and Harris (1920), which considers the lower necessary tunnel speed to achieve the same thrust and torque. So this correction method gives the equivalent open water velocity depending on the thrust loading of the propeller $C_{TH} = \frac{T}{((\varrho/2)u^2\pi R^2)}$ and the ratio between propeller disk area and the cross section area of the tunnel as an indication of the blockage. This result in the needed J' and a in consequence to $\eta' = J' \cdot \frac{K_T}{(2\pi k_Q)}$. The tunnel thrust coefficient $k_T = \frac{T}{(\varrho n^2 D^4)}$ and the tunnel torque coefficient $k_Q = \frac{Q}{\varrho n^2 D^5}$ undergo a shift according to the difference between J and J'.

4 TEST RESULTS

The tunnel tests for the propellers P2004 and P2671 were carried out for several shaft speeds (see: Table 1), the measurements for each condition were carried out three times.

Table 1: Table 1

Propeller 2671		Propeller 2004	
Rn_{07R}	$speed$	Rn_{07R}	$speed$
		$0.77 \cdot 10^6$	$6Hz$
$0.53 \cdot 10^6$	$12Hz$	$1.53 \cdot 10^6$	$12Hz$
$0.66 \cdot 10^6$	$15Hz$	$1.92 \cdot 10^6$	$15Hz$
$0.79 \cdot 10^6$	$18Hz$	$2.30 \cdot 10^6$	$18Hz$
$1.19 \cdot 10^6$	$27Hz$		
$1.58 \cdot 10^6$	$36Hz$		

Based on the open water tests results we investigated the influence of the various methods on the full scale values of thrust and torque. The consideration of laminar flow phenomena can be excluded as all methods give the recommendation to scale only open water results showing a characteristic Rn_{07R}-number higher than $5 \cdot 10^5$.

Figure 4 shows results from the large tunnel for the larger geometry for propeller 2004 after Wood & Harris correction (shorter curves). A geometrical similar smaller propeller was tested in the Towing Tank (curves starting at

$J' = 0$). A dashed line for K_T gives the uncorrected results and demonstrates the shift imposed by the correction. The propeller 2004 was an ideal candidate for tunnel tests because of its large dimensions.

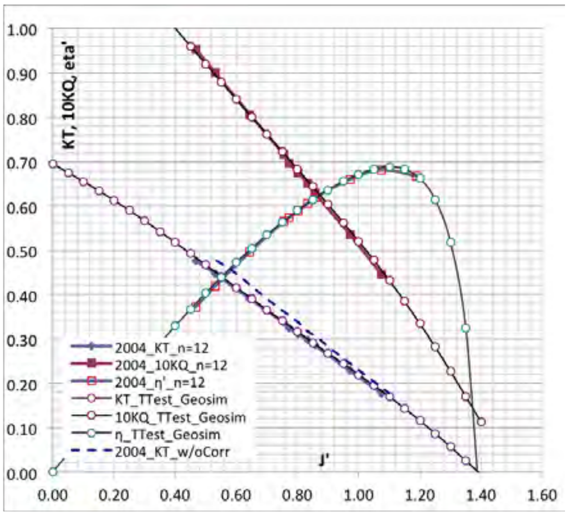

Figure 4: Open water result propeller 2004

Figure 5 gives the comparison of tank- and tunnel results for propeller 2671 for a speed of 17Hz in the tank and 27Hz in the tunnel.

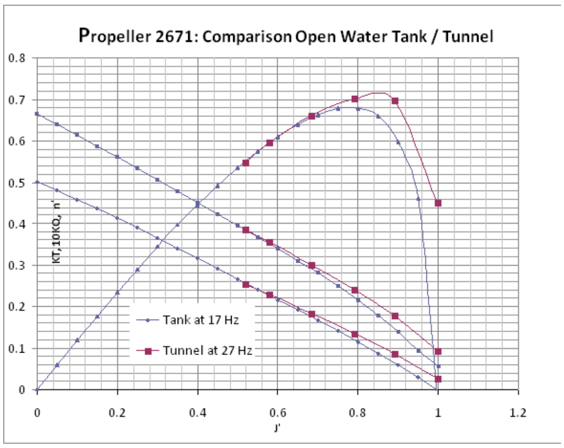

Figure 5: Open water result propeller 2671

5 LOW ORDER SCALING PROCEDURES

The correction of the measured open water values towards the conditions at full scale is carried since many decades by use of different more or less simple algorithms.

The ITTC'78 method (1978) for example deduces scale effects from the prediction of tangential forces acting on the blade sections in either scale. This method is generally not completely covering the presence of viscous effects. In addition to this constriction only the section at 75% of the propeller radius is used as a representative for all other radii. The essential outcome of the ITTC procedure is an incremental friction coefficient Δc_f that converts model scale data into their full scale equivalents by increasing thrust ($K_{T,FS} = K_{T,MS} + \Delta K_T$) and lessening torque ($K_{Q,FS} = K_{Q,MS} + \Delta K_Q$) according to the blade roughness.

The Meyne-Method (1968) used at HSVA shows differences from the ITTC procedure as it starts with deriving a combination η_i, C_{THi} representing the friction-less and optimum propeller, i.e. the ideal propeller. The information entering from the model tests is the couple η, C_{TH}. The parameter which controls the conversion from η, C_{TH} towards η_i, C_{THi} and which is to be adjusted by iteration for a consistent transformation is ϵ_{07}, a percentage of the ideal lift force acting as drag on the representative radius (0.7R). Prescribing ϵ_{07}, one can obtain η_i from η as well as C_{THi} from C_{TH}, however, according to the Kramer diagram (1939), there is only one valid combination η_i, C_{THi}. The essential outcome of the Meyne-Method is the ideal efficiency η_i which, when applying a full scale friction coefficient $c_f^* = 0.006$ (and typically small estimates for additional pressure drag), reduces to the full scale efficiency η^*.

6 HIGH ORDER SCALING PROCEDURES

A propeller surface panel method can give the inviscid efficiency η_{in} in a natural way as it is based on inviscid flow principles. In this view it is linked to the lifting line approach, commonly used to define the ideal performance of conventional propellers. With a panel method a circulation $\Gamma(r)$ is readily obtained for any open water setup. Thus the panel method builds the 'bridge' between lifting line (dealing with the performance related to a prescribed circulation $\Gamma(r)$) and the actual geometry (hiding its lifting line character behind geometrical data like pitch, chord and camber). On the other hand, lifting line principles may help to adjust the free vortex wake for the panel in s simple and reliable manner.

The panel method applied here (Streckwall, 1998) for the estimation of the full scale efficiency includes a lifting line based iteration leading to vortex wake alignment. We make use of the fact that the lifting line approach reads the ideal efficiency η_i from the constellation of incoming and induced velocity components. Formally we get a η_i-equivalent from the panel method by evaluating and summing forces and moments from each blade element. We obtain the efficiency $\eta_{in} = uT_{in}/(2\pi n Q_{in})$ (not ideal but inviscid) and use it for a global estimation of the vortex wake behavior. We adjust our trailing vortex pitches $tan\beta_t(r)$ to the sum of incoming and induced velocity components ($u + \Delta u(r)$ and $\omega r + \Delta v_T(r)$). Assuming the same constellation as for an ideal propeller with a efficiency $\eta_i = \eta_{in}$ we set $tan\beta_t(r)tan\beta_i(r) = tan\beta(r)/\eta_i$ close behind the blade and double the difference between $tan\beta_i(r)$ and $tan\beta(r)$ for the pitch in the developed slipstream.

In some sense the panel method is a sophisticated Meyne-method taking into account also non-optimum open water performance, strictly operating according to the provided geometrical data (leading to an inviscid efficiency η_{in}, not necessarily equal to the ideal efficiency η_i). As a prospect, introducing a non-uniform but still circumferentially symmetric inflow, the panel method may analyze the actual propeller in a more favorable environment and function as an alternative source for the relative rotational efficiency labeled as η_R and appearing in the decomposition of the overall propulsion efficiency η_D. A panel method may however hardly operate as part of a "recommended" propeller scaling procedure.

Also the RANS approach can hardly be introduced as a fixed part of a standard scaling procedure. Within a research project however RANS calculations provide useful insights and alternative results. Using RANS we determined the model scale and full scale efficiency of the tested propellers. In our RANS calculations performed with the FreSCo+ code (Schmode and Hafer-mann 2006, Schmode et. al. 2006, Hafermann 2007) the standard k-ϵ turbulence model of Wilcox was applied.

In FreSCo+ we have the possibility to separate forces acting on the blade surface to into a tangential and a normal component. However the normal component will not be of true inviscid nature. It will include pressure drag due to viscous effects. The tangential component will express the magnitude and the direction of the shear stresses at the bottom of the boundary layer. The latter may be influenced by centrifugal forces. Formally a RANS calculation with "slip wall" condition on the blade surface (supported by a strong reduction of the kinematic viscosity) could derive an alternative result for the inviscid efficiency η_{in} is reflecting the principles could establish a link to the panel method.

7 DERIVING TRENDS FROM THE MODEL TEST

Figure 6 and Figure 7 give an evaluation of the test results to identify a trend for the measured efficiency against the Reynolds-number.

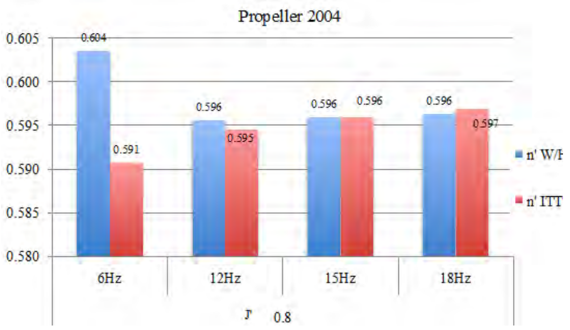

Figure 6: Analysis of effect of Rn-number change propeller 2004

For each propeller we concentrate on just one point in the open water diagram. To have an idea for an expected tendency we used the ITTC'78 scaling method and relied on their friction line for model scale.

For propeller 2004 we enforced matching at 15Hz (quasi presenting these results as measured results) and obtained Δc_f values to relate n=15 to every other frequency (characterized by a different Reynolds which then becomes a target for scaling). The difference in surface friction Δc_f was then converted into equivalent increments ΔK_T and ΔK_Q according to the ITTC-formulas. Excluding the lowest shaft frequency, which clearly showed the largest scatter for repeated tests, the measured efficiencies hardly changed with Reynolds number. The ITTC scaling procedure would expect roughly a 0.5% gain in efficiency from 6Hz to 18 Hz.

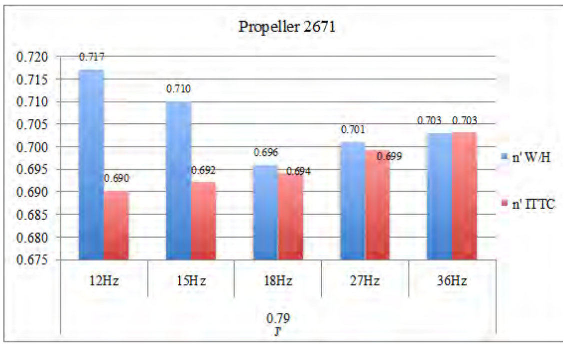

Figure 7: Analysis of effect of Rn-number change propeller 2671

For the propeller No. 2671 we set up a similar procedure, however presenting the 36Hz results as the basis for the ITTC scaling procedure and using every other frequency as the target for a (downwards) scaling process. Again the measured efficiencies related to the higher frequencies show a tendency to follow the trend given by the ITTC-method. However the Reynolds number dependence of the measured efficiencies is weaker.

8 FULL SCALE EFFICIENCIES

All of the used methods refer to the performance of an inviscid propeller. The method of Lerbs/Meyne derives the performance of interest directly from η_i, wheras the ITTC method uses the model scale friction line. At the Panel method the genuine uncorrected result is to be found and the RANS can be used by excluding the tangential surface forces. For all methods the difference in K_Q between this inviscid state to full scale respectively model scale can be evaluated.

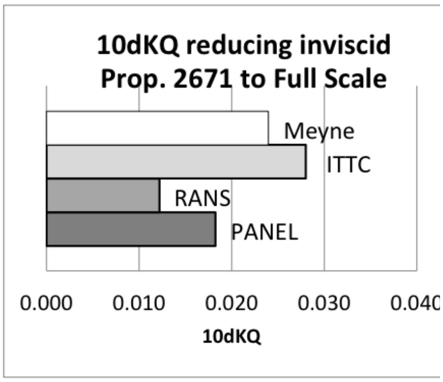

Figure 8: 10dKQ towards full scale propeller 2671

Figure 8 and Figure 9 gives the result from such a procedure, taking thrust and torque data from the propeller 2671 related to an equivalent advance coefficient $J' = 0.7$, a value not far from the design condition of this propeller. A large scatter in torque for the step from the inviscid propeller to full scale can be derived, whereas the differences for the further step to model scale are lower.

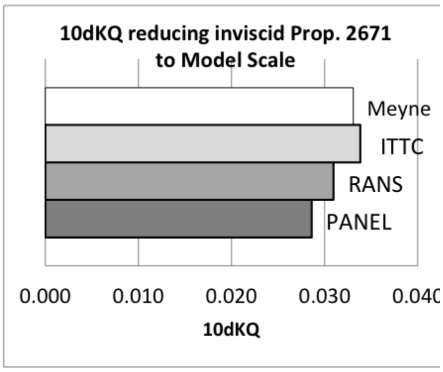

Figure 9: 10dKQ towards model scale propeller 2671

As K_T is usually less sensitive to friction, the behavior of the efficiency follows this trend, which is expressed in Figure 10.

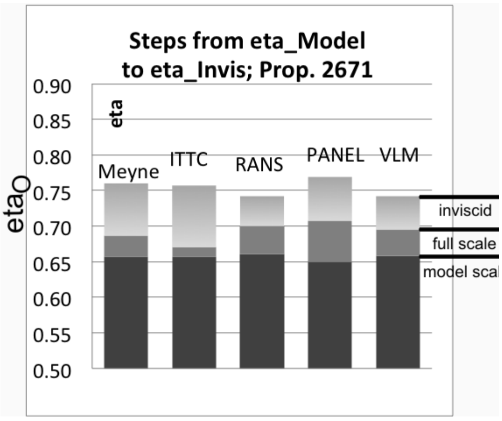

Figure 10: different η_O levels of propeller 2671

Here we built up the efficiency stepwise from model scale level to full scale top. The lowest level is the model propeller efficiency, which resembles the measured one in case of the ITTC- and Meyne-method and is calculated otherwise. The next level represents the predicted full scale efficiency while the tops of the columns reach the predicted inviscid efficiency. With ”VLM” a vortex lattice method was included, which necessarily counts all forces strictly normal to the cambered but otherwise plate-like substitute of the real blade section. This could lead to an underestimation of the inviscid efficiency. In Figure 10 the scatter of predicted efficiencies reflects the scatter in torque correction for propeller 2671 at 18Hz and $J' = 0.79$.

All RANS calculations were run in an unsteady mode using time stepping to arrive at a settled performance. All RANS simulations were further done in a tube showing the same diameter as the test section of the tunnel. Accordingly we corrected the RANS results as if they were tunnel measurements, i.e. we derived a free field equivalent advance coefficient J'.

In Figure 11 and 12 the difference in surface pressure level $C_p = (p - p_o)/(\rho n^2 D^2)$ between model scale and full scale is shown. No significant difference for this quantity appears. For propeller 2671 one may notice the strong gradient from high pressures at the leading edge to low pressure on the remaining part of the blade occurring at the inner sections. This is typical for a wake adapted propeller becoming subject to homogeneous inflow.

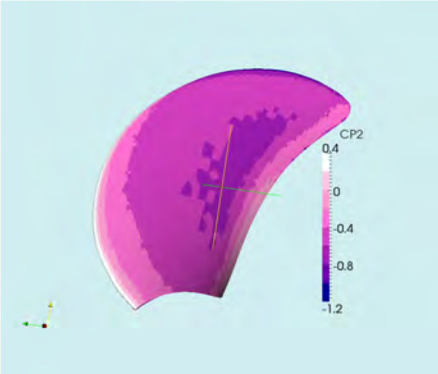

Figure 11: suction side cp on model scale propeller 2671

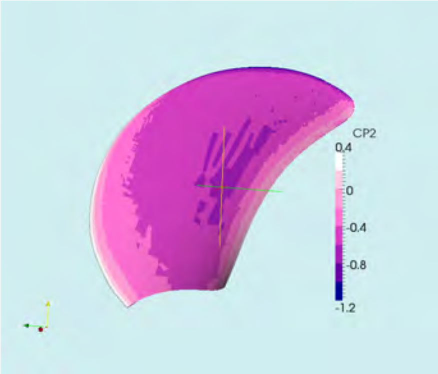

Figure 12: suction side cp on full scale propeller 2671

9 ADVANCED SCALING PROCEDURE

The main target of the project ”PREFUL” was to develop an advanced scaling mehod with the aim to be robust, fast but sensitive even for unconventional propeller geometries. The realisation was carried out by a strip method considering a sectioning according to figure 13.

Figure 13: schematig diagram of strip method

Based on RANS results for several propellers an empiric model was derived in order to divide the surface of the propeller in areas with laminar flow and therefore small effect on the tangential force and turbulent areas with higher influence on the tangential force. For the determination of these areas with different flow the strip method was used as a ”surface element method” (see: figure 14).

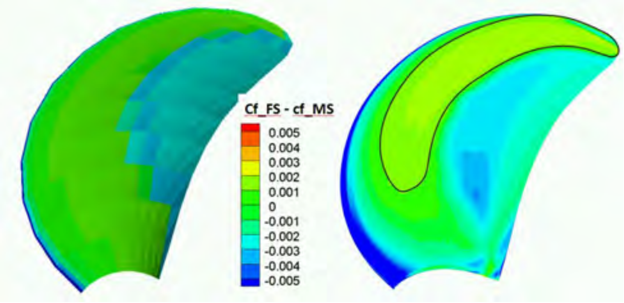

Figure 14: difference of local friction coeffitions

The figure shows the good coverage of the assumption based on the strip method and differences between full scale and model scale local friction coefficients based on RANS-calculation considering the transition.

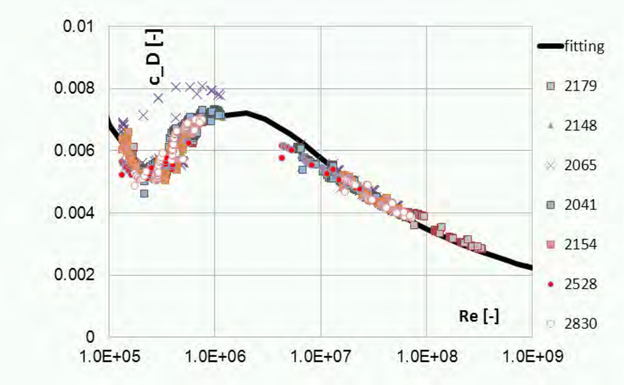

Figure 15: RANS based friction line

In order to feed the strip method for more robust assumptions a new specific friction line was derived from the RANS results of several propellers. Figure 15 shows the result of seven different propellers. Every data point in the diagram represent the fristional resistance coefficient for one radius of one propeller in one specific model scale. As a ”fitting” a trend line can be captured and be used as a basis for the strip method.

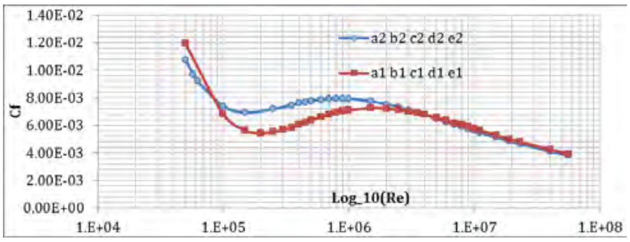

Figure 16: friction lines for strip method

In order to consider the realistic ranges of Reynolds numbers resulting for the propulsion test notwithstanding this derived friction line a new more turbulent line was used for the calculation of the conditions behind the model ship. Figure 16 shows both necessary friction lines.

Based on these strip method a new prediction for the open water efficiency was carried out for propeller 2671. Figure 17 shows the corrected open water curves for full scale (FS) and for the relations during the propulsion test (ProT).

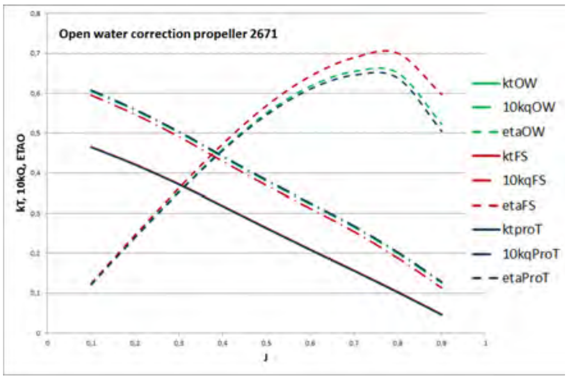

Figure 17: strip method results for propeller 2671

10 CONCLUSIONS

Based on a review of existing scaling methods for propeller efficiency the differences between the single methods are significantly. This underlines the demand of a modernisation of the scaling procedure. The comparison was supported by open water tests at high Reynolds numbers performed in a large cavitation tunnel. The efficiency of an inviscid propeller can be derived from all used calculation methods. Based on the (high Reynolds) result of 3 propellers examples all used scaling methods predict this virtual propeller with a very good agreement. There was a larger deviation in the prediction of the full scale propeller open water efficiency due to the usage of different friction lines (lower order procedures and panel method) and friction concepts (RANS).

In order to enhance the correction procedure of open water results towards the full scale conditions as well as the conditions to be found at the propulsion test a strip method was developed based on two different friction lines representing each on of the focused conditions. The friction line was directly derived from RANS calculations for several different propeller geometries and setups. For a better prediction accuracy the results of the enhanced open water correction are to be evaluated with full scale observations (trial trips).

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