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A Method for Scale Effect Corrections on Pod Propulsor Open Water Characteristics from Model to Full Scale

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1 Introduction

Pod drives have been used as propulsion units for ships for about 15 years. Due to several advantages such as more space for pay load, better manoeuvrability and lower noise level, pod drives have been implemented primarily on twin screw vessels like cruise liners and ferries.
In conjunction with the development of pod drives, a corresponding model testing technology has evolved and the number of model tests with pod drives has increased significantly. Each of the towing tanks involved has developed its own conversion method for the extrapolation of model results to full scale (e.g. Holtrop(2001)). An ITTC recommendation is not yet available.
HSVA has developed a practical method for the conversion of the model pod open water data to full scale. The method described in this paper is based on experience available in the scaling of passive components of the propulsion train, see also Eaton, Praefke, Mewis (2003), and incorporates a proven scaling method for the propeller itself. The conversion is broken down into two independent steps: The first deals with the scale effects on the propeller alone and the second with friction effects on the pod housing with the propeller working.

Fig. 1 Cruiseliner „Radiance of the Seas" driven by two Pod-Units, Azipod, 2x20 MW (courtesy of Jos. L. Meyer Yard, Papenburg)

2 Model Tests with Pod Driven Ships

Model Tests with pod driven ships require special thrust and torque sensors, a special methodology for the tests and a special scaling method for the open water characteristics of the pod drives. All other methodology can be used as usual, for instance by using the ITTC-1978 powering performance prediction method. In this chapter, a short description of the test methodology as used at HSVA for resistance, self propulsion, propeller open water and open water unit tests will be presented.

2.1 Resistance Tests

At HSVA, the resistance tests for pod driven ship models are carried out in bare hull condition, i.e. without any appendages and also without the pod unit. The openings of the pod shafts are closed.
Measured quantities:
V - model speed
$R_{T(bare)}$ - model resistance, bare hull

2.2 Self Propulsion Tests

For the self propulsion tests, the ship model is equipped with the whole pod unit. For that reason an opening in the model is a need where the driving shaft has to be passed through. The opening in the model for the driving shaft has to be as small as possible, 5 mm gap around the shaft is a good value. The distance between the upper

part of the shaft and the model surface should be less than 5 mm. This arrangement is in opposite to full scale because in model scale the thrust of the unit has to be measured with a balance situated inside the ship model.
The wetted surface of the pod units has not to be included in the surface used for the estimation of the skin friction correction.
Measured quantities:

V - model speed
n - propeller rate of rotation
Q - propeller torque
T_{unit} - total thrust of the pod unit

The propeller thrust can be measured, but the results might be misleading due to the influence of the gap behind the conical hub (Mewis, 2001; ITTC, 2002). They should be used with utmost care, if at all.
The measurement of the transverse force of the pod unit is helpful but is not a need for the scaling procedure.

F_Y - transverse force of the pod unit

Fig. 2 Pod units installed on a twin-screw ship model

2.3 Open Water Tests with the Propeller Alone

In any case it is a need to carry out propeller open water tests with the propeller alone. The test procedure is well known and should not be described here. Special attention must be paid to the conical hub of the propeller. Figure 3 illustrates the recommendation of the ITTC 2002.

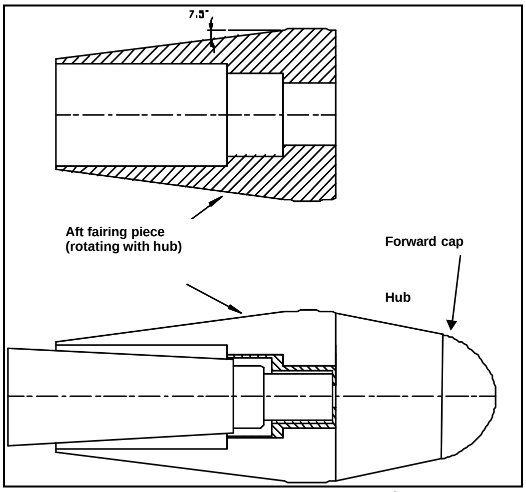

Fig. 3 ITTC 2002 recommendation for pod propellers at propeller open water test (ITTC, 2002)

Measured quantities:

V - advance speed
n - propeller rate of rotation
Q - propeller torque
T - propeller thrust

2.4 Open Water Tests with the Pod Unit

A special device is needed for open water tests with pod units. The HSVA solution is described below.
Measured quantities:

V	- advance speed
n	- propeller rate of rotation
Q	- propeller torque
T_{unit}	- total thrust of the pod unit

During the measurement of the propeller thrust, the same problem arises as described under item 2.2, the measured values are influenced by the gap behind the conical hub.
HSVA is carrying out the open water unit tests with a so called propeller boat (see Fig. 4). The bottom of the propeller boat is above the water surface. The electrical motor and the balance for the unit thrust measurement are mounted inside the propeller boat.

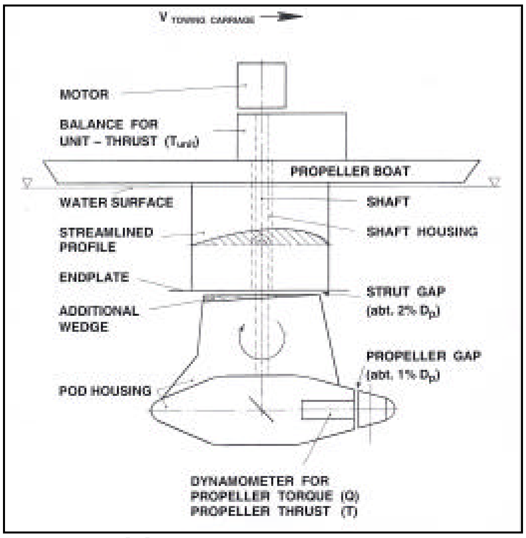

Fig. 4 Pod drive in open water unit test (Mewis, 2001)

The propeller is driven by the motor at the top via a gear drive in the same manner as in the propulsion test. In order to avoid any influence of the water surface, the propeller shaft must be submerged at least 1.5 x D_P, preferably 2 x D_P. The free part of the model drive shaft between the upper end of the pod strut and the bottom of the propeller boat must be covered by a streamlined profile in order to avoid drag on the shaft itself. This profile is fixed to the bottom of the propeller boat (Fig. 4).The bottom of the profile is fitted with a thin endplate in order to minimize the effects in the strut gap. The endplate is arranged parallel to the water surface.
The bottom of the propeller boat has to fly 5 to 10 mm above the water surface in order to avoid waves caused by the strut piercing the surface.
The propeller shaft must be arranged parallel to the water surface. In most cases this arrangement leads to an open wedge at the upper, aft end of the pod strut. This open part should be filled out with an additional wedge in order to make the upper surface of the pod strut parallel to the endplate of the streamlined profile and to ensure an uniform strut gap.
The width of the propeller gap has an unavoidable, large influence on the measured propeller thrust. For that reason it is very important to have fixed rules for the gap width. The recommended width of the propeller gap amounts to about 1% of the propeller diameter. The propeller gap width does not influence the unit thrust.
The width of the strut gap has a small influence on the measured thrust of the unit. This gap must be parallel to the water surface. The recommended width of the strut gap is about 2% of the propeller diameter.
The thrust and torque of the propeller, T and Q, are measured using a dynamometer on the propeller shaft located as close to the propeller as possible in order to avoid mechanical friction effects. The thrust of the whole unit, T_{unit}, is measured using a balance at the junction between the strut and the propeller boat. The propeller boat is fixed to the towing carriage. The rotation rate of the propeller, n, and the velocity of the towing carriage are measured in the usual manner.

3 Evaluation Method for Resistance and Self Propulsion Test Results

The evaluation of the resistance and self propulsion test results is following the same procedure as for conventionally propelled ships. However, the propulsive factors have to be defined using the pod unit thrust T_{unit} and the bare hull resistance $R_{T(bare)}$:

Thrust deduction fraction:

$$t = \frac{T_{unit} - R_{T(bare)}}{T_{unit}}$$

with T_{unit} - thrust of pod unit
$R_{T(bare)}$ - bare hull resistance

Wake fraction, thrust identity:

$$W_T = \frac{J - J_{T(unit)}}{J}$$

with J = $V / (D \cdot n)$, from self propulsion test
$J_{T(unit)}$ - advance ratio determined from pod unit open water test thrust identity
D - propeller diameter
n - propeller rate of rotation

Wake fraction, torque identity:

$$W_Q = \frac{J - J_Q}{J}$$

with J_Q = advance ratio determined from pod unit open water test torque identity

Hull efficiency:

$$h_H = \frac{(1-t)}{(1-W_T)}$$

Unit open water efficiency:

$$h_{OT} = \frac{K_{T(unit)}}{K_{Q(T)}} \cdot \frac{J_{T(unit)}}{2p}$$

with $K_{T(unit)}$ = $T_{unit} / ?n^2D^4$, from self propulsion test
$K_{Q(T)}$ - K_Q at $J_{T(unit)}$
$?$ - mass density

Propulsive efficiency:

$$h_D = \frac{P_{E(bare)}}{P_D}$$

Relative rotative efficiency:

$$h_R = \frac{h_D}{h_{OT} \cdot h_H} = \frac{K_{Q(T)}}{K_Q}$$

with $K_{Q(T)}$ - K_Q at $J_{T(unit)}$ in pod unit open water characteristics
K_Q = $Q / ?n^2D^5$, from self propulsion test

4 Evaluation Method for Propeller Open Water Characteristics

HSVA is using their own propeller open water correction method based on Lerbs theory, developed and introduced by Meyne (1972). A brief description of this „Method of equivalent profile“ is given in appendix A. The estimated $?K_T$ and $?K_Q$ values between the Reynolds number of the propeller open water test and full scale will be used for the correction of the pod open water characteristics.

$?K_{T(propeller)} = K_{T(full\ scale)} - K_{T(model\ scale)}$

$?K_{Q(propeller)} = K_{Q(full\ scale)} - K_{Q(model\ scale)}$

The $?K_T$ and $?K_Q$ values can also be determined using the ITTC-1978 method, or any other suitable method.

5 Evaluation Method for the Pod Unit Open Water Characteristics

In the hydrodynamic sense, the pod unit consists of two main parts, the propeller and the pod housing. Accordingly, the scale effect correction procedure is separated for these two parts.
In the first step, the propeller torque and unit thrust are corrected by the $?K_Q$ and $?K_T$ values determined from the propeller open water test as described above.
In the second step, the drag of the pod housing is corrected by using a simplified strip method. This method can be used for propulsion units in general (Praefke, 1994).
The method proposed simplifies the problem in several ways:

- The influence of the swirl in the propeller slipstream is neglected.
- The propeller-induced axial velocity in the slipstream is assumed to be independent of the radius.
- The method does not account for different lift curve slopes of a profile section at different Reynolds numbers.
- The method does not include the shift of transition lines from laminar to turbulent flow at different Reynolds numbers.

Within the method proposed, the friction forces and their influence on the pod housing drag are integrated stripwise over several "zones" of the pod housing. Where applicable, the additional velocity in the propeller slipstream is taken into account. Each zone is characterized by its length c_i and its surface S_i.

The four zones of a pod housing are the following:
Zone A: Upper part of the vertical strut, outside the propeller slipstream (i.e. above the propeller tip in upright blade position)
Zone B: Lower part of the vertical strut, inside the propeller slipstream (i.e. the remaining part of the vertical strut)
Zone C: The „bomb" of the pod housing, containing the electric drive motor, inside the propeller slipstream
Zone D: Any fins mounted on the „bomb", inside the propeller slipstream

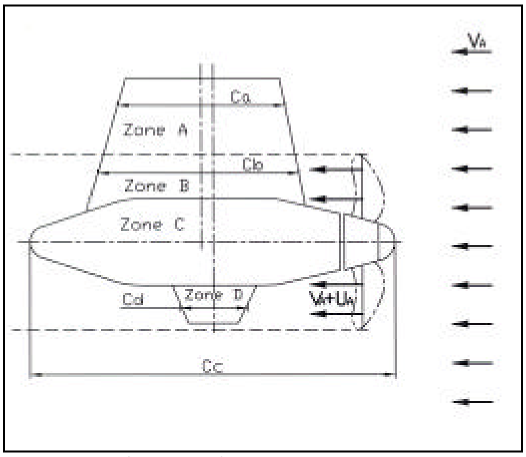

Fig. 5 Definition of Pod Housing Zones

The inflow velocity to a zone is

either: $V_i = V_A = J\, n\, D$
with V_A = propeller advance speed
J = advance coefficient
n = shaft speed
D = propeller diameter
(if the zone under consideration is located outside the propeller slipstream)

or: $V_i = V_A * (1+C_{Th})^{0.5}$
with C_{Th} = propeller thrust loading coefficient
(if the zone under consideration is located inside the propeller slipstream)

The Reynolds number of a zone is
$R_{n,\,i} = V_i\, c_i \,/\, ?$
with $?$ = kinematic viscosity of water
c_i = mean length in each zone

During the model manufacturing, the surface of the pod housing has been carefully grinded. Thus, a hydraulically smooth surface at the model Reynolds number can be assumed. For the determination of the friction forces on each zone of the pod housing, the friction coefficient C_F can either be prescribed or it can be determined as a function of the Reynolds number, for example by use of the Schoenherr formula for fully turbulent flow:

$log_{10}(R_n\ C_F) = 0.242 / (C_F)^{0.5}$

The full scale pod housing surface is considered to be hydraulically smooth as well, implying a reasonably low average surface roughness.

In case of the assumption of hydraulically not smooth surfaces, different friction coefficients have to be applied: According to Schlichting (1982), the allowable surface roughness k amounts to

$k_{allowable} = 100 * c_i / R_{n,\ i}$

If the actual surface roughness exceeds this limit, the resulting friction coefficient is no longer dependent on the Reynolds number and may instead be determined by

$C_F = (1.89 + 1.62 * log_{10}[c_i/k])^{-2.5}$

Hence, the friction force on a zone equals

$F_i = 0.5\ ?\ C_{F\ i}\ V_i^2\ S_i$

with $?$ = density of water

The zone friction force‘s influence on the propeller thrust coefficient is

$K_{T,\ F\ i} = F_i / (?n^2\ D^4)$

The entire friction influence on K_T is obtained by summing up over the pod housing zones:

$K_{T,F} = S K_{T,F\ i}$

The above procedure is executed twice, once for model scale conditions and once for full scale conditions. The correction of the pod housing drag can be estimated:

$?K_{T(drag)} = K_{T,F(full\ scale)} - K_{T,F(model\ scale)}$

The correction of the pod unit open water characteristics can be summerized:

$K_{Tunit(full\ scale)} = K_{Tunit(measured)} + ?K_{T(propeller)} + ?K_{T(drag)}$

$K_{Q(full\ scale)} = K_{Q(measured)} + ?K_{Q(propeller)}$

Fig. 6 shows an open water diagram of a typical pod unit. The measured K_{Tunit} and K_Q values are shown for model scale as well as the two steps of corrections to full scale.

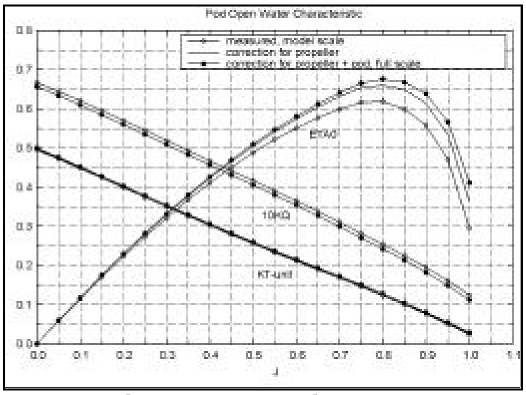

Fig. 6 Pod unit open water characteristics

6 Summary/Conclusion

The paper describes the testing methodology for pod driven ship models as applied at HSVA.

A simplified application of the “Surface Strip Method” for extrapolating the pod housing drag from model scale to full scale has been introduced. This method is used regularly at HSVA and proved to be accurate enough for the practical use.

The proposal to separate the pod housing in 4 zones can be extended if needed for additional parts of new pod designs. The method is suitable for parts of propulsion devices in general.

HSVA has accumulated experience using this method for some years. Correlation of model scale test data with full scale data leads to the conclusion that this method provides reliable results in full scale prediction. This method of scaling is better than a simple percentage drag correction, especially for pods with small fins or short and blunt pod housings.

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Appendix A:
Brief description of the "Method of equivalent profile" for the determination of scale effects on propeller open water tests

The described method is based on Lerbs theory, developed and introduced in HSVA by Meyne (1972).
The propeller open water test results are analysed using optimum propeller theory equations. The "equivalent profile" at 70% radius is taken as representative for the whole propeller. The aim of this analysis is to evaluate a certain friction coefficient which is then corrected for different Reynolds numbers or different surface roughness conditions. In a second step, the analysis procedure is reversed in order to obtain the corrected open water characteristics.
The analysis procedure is the following:
For each advance coefficient J or $? = J/p$ tested, an iteration is performed in order to determine the ideal advance coefficient $?_i$. The iteration starts with an ideal thrust loading coefficient $C_{Th,i}$ $(J) = C_{Th}$ (J).
The ideal efficiency $?_i$ can be read off Kramer's table (1938) as a function of ?, blade number Z, and $C_{Th,i}$. Hence, the first value for $?_i$ equals $?/?_i$. For optimum propellers, the lift to drag ratio at the equivalent radius 0.7 R can be calculated:

$$e_{0.7} = \frac{1 - \frac{h}{h_i}}{\frac{2}{3} \cdot \frac{h}{l} + 2 \cdot l_i}$$

According to von Kármán and Bienen, a second ideal thrust loading coefficient can be determined:
$C_{Th,i} = C_{Th} / (1 - 2 \cdot e_{0.7} \cdot ?_i)$

which generally is different from the first one. Hence, one obtains a different ideal efficiency h_i and the above calculations are performed several times until convergence between both of the two ideal thrust loading coefficients is achieved.
After having evaluated $?_i$, one can calculate the ideal hydrodynamic pitch angle
$ß_{0.7,i} = \text{atan}(?_i / 0.7)$,

the lift coefficient

$$C_{L0.7} = \frac{4 \cdot p}{Z} \cdot \frac{0.7 \cdot k_{0.7} \cdot \sin b_i \cdot \tan(b_i - b)}{\frac{c}{D_{0.7}} \cdot [1 - e_{0.7} \cdot \tan(b_i - b)]^2}$$

and the drag coefficient
$C_{D\,0.7} = e_{0.7} \cdot C_{L\,0.7}$.

Plotting the analysed values $C_{D\,0.7}$ versus the advance coefficient J, one obtains a parabola-shaped curve with a distinct minimum value $C_{D\,\min}$ which normally lies near the design advance coefficient. Assuming a shock-free entrance at the equivalent profile at this advance coefficient, i.e. no pressure drag, the characteristic flat plate friction coefficient valid for the whole open water test is then determined by
$2 \cdot C_F = C_{D\,min} / [1 + 2(t/c)_{0.7} + 60 \cdot (t/c)_{0.7}^4]$
(where the factor two accounts for each of the two blade sides).

The pressure drag coefficient C_P for each of the advance coefficients is then
$C_P(J) = C_D(J) - C_{D\,min}$.

In a second step, the above procedure is reversed:

First, a characteristic full scale friction coefficient C_F‘ is determined, depending on Reynolds number and surface roughness. For hydraulically smooth surfaces, the friction coefficient C_F‘ can be determined as a function of the Reynolds number, for example by use of the Schoenherr formula for fully turbulent flow:
$log_{10}(R_n\, C_F) = 0.242 / (C_F)^{0.5}$

According to Schlichting (1982), the allowable surface roughness k amounts to
$k_{allowable} = 100 \cdot c_{0.7R} / R_{n\,0.7Ri}$

If the actual surface roughness exceeds this limit, the resulting friction coefficient is no longer dependent on the Reynolds number and may instead be determined by
$C_F' = (1.89 + 1.62 \cdot log_{10}[c_{0.7R}/k])^{-2.5}$

Generally, a value of $C_F' = 0.0030$ is assumed according to a Reynolds number of approximately 10^7 or a corresponding surface roughness k. The characteristic profile drag coefficient valid for full scale follows from
$C_{D\,min}' = 2 \cdot C_F' / [1 + 2(t/c)_{0.7} + 60 \cdot (t/c)_{0.7}^4]$.

Then, the full scale drag values
$C_D'(J) = C_{D\,min}' + C_P$

are calculated, using the same pressure drag coefficient C_P as analysed from the model test:
$C_P'(J) = C_P(J)$.

It is further assumed that there is no scale effect on the lift coefficients:
$C_L' = C_L$.

Then the full scale drag to lift ratio can be obtained as
$e_{0.7}' = C_{D\,0.7}' / C_{L\,0.7}$.

Finally, the corrected thrust and torque coefficients are calculated by

$$K_{T,\,full\,scale} = K_{T,\,modelscale} \cdot \frac{1 - 2 \cdot e_{full\,scale} \cdot l_i}{1 - 2 \cdot e_{modelscale} \cdot l_i}$$

$$K_{Q,\,full\,scale} = K_{Q,modelscale} \cdot \frac{1 - \frac{2}{3} \cdot e_{full\,scale} \cdot l_i}{1 - \frac{2}{3} \cdot e_{modelscale} \cdot l_i}$$

The $?K_T$ and $?K_Q$ values are to be estimated in the following manner:
$?K_{T(propeller)} = K_{T(full\ scale)} - K_{T(model\ scale)}$
$?K_{Q(propeller)} = K_{Q(full\ scale)} - K_{Q(model\ scale)}$

HSVA has used this method for many years and claims it to be far more scientific than the ITTC 1978 method. Moreover, with this method it is easily possible to detect and account for rough model propeller surfaces which is not included in the ITTC 1978 method.

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