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On the advanced extrapolation method for a new type of podded propulsor via CFD simulations and model measurements

Tomi Veikonheimo[1]**, Pasi Miettinen**[1]**, John Huisman**[2]

[1]ABB Marine and Ports, Helsinki, Finland

[2]Maritime Research Institute Netherlands (Marin), Wageningen, Netherlands

ABSTRACT

A method for the full scale extrapolation of model scale measurements on a multi component podded propulsor is presented. The scaling is based on model measurements in which nozzle and stator, propeller and the unit forces were measured. Those can be extrapolated separately with the aid of actuator disk theory and CFD computations. With a practical example based on the newly developed ABB Azipod® XL, model scale measurements, CFD calculations and the extrapolation procedure are discussed in this paper.

Keywords

Model scale measurements, CFD, extrapolation, podded propulsion, actuator disk theory.

1 INTRODUCTION

Recently, ABB launched the new Azipod® XL (Figure 1), a Linear Flow Propulsor Azipod (LFP) as a continuation in the Azipod propulsion unit series. The Azipod® XL can be considered as a major step in the improvement of the existing Azipod® XO series’ hydrodynamic performance.

The main benefit of the Azipod® XL is improved hydrodynamic efficiency. This is achieved by installing a special nozzle module to a pulling Azipod. Six stator blades behind the propeller support the nozzle. The fixed stator blades straighten the water flow from the propeller. Hence, turbulence and energy loss will be reduced such that higher thrust is provided to propel the ship. The geometry and alignment of the stator blades are designed to minimize tangential flow component in the flow and at the same time support all hydrodynamic loads from nozzle.

ABB and MARIN have been working together to establish a reliable, robust and practical extrapolation method to provide a full scale performance prediction. For this kind of multi-component propulsion device the separate parts of the unit require different scaling or extrapolation from model scale to full scale. The method has been developed based on both model measurements as performed at MARIN and CFD calculations (Figure 2) as performed by ABB. By combining these two datasets, MARIN applied a scaling method to estimate the full scale ship performance with this kind of new podded propulsion units.

Figure 1: Azipod® XL podded propulsor.

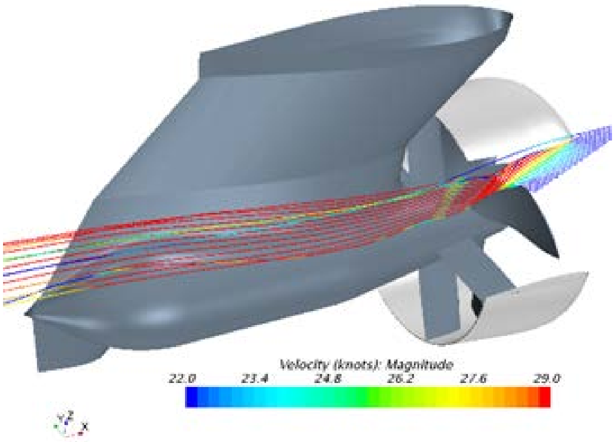


Figure 2: CFD flow lines behind the stator blades along the pod unit.

When comparing two different pod units with different shapes, wetted areas and appendages, the mutual comparison of extrapolated results should be as accurate as possible. It might be that model scale measurements yield similar performance, but that one concept performs significantly better at full scale.

Open water characteristics of podded propulsors as measured on model scale should be corrected for Reynolds scale effects. At MARIN the POD-U method has been developed which takes into account the differences in the size and shape of the pod housings. This method leads to scale effect corrections depending on speed and loading by means of actuator disk theory and a friction line. The local velocity on the pod housing and the form factor are governing factors. This method has been widely used and accepted for conventional podded propulsors without nozzle and stator blades. In this paper, an historical overview of extrapolation methods for podded propulsors will be presented.

In this work, the POD-U method has been expanded. Dedicated measurements and CFD computations are required due to the mutual interaction between propeller, pod housing, nozzle and stator blades.

MARIN measured the thrust and torque delivered by the propeller, and, separately, the thrust and torque delivered by the duct and integrated stator blades. Furthermore, the unit forces were measured in a 6-component frame. The open water characteristics could therefore be corrected for scale effects on the resistance of the pod strut and torpedo, and separately for scale effects on the resistance of the duct and post-stator blades. The corrected characteristics are input for the extrapolation of the self-propulsion model scale measurements.

In CFD, for each component of the pod (nozzle, torpedo, strut, stator, stator fins) the local velocity and form factors are extracted. Open water performance of this pulling type Azipod thruster is computed by unsteady RANS CFD simulations at full and model scales.

In this paper, the need for advanced experiments at model scale and dedicated CFD computations both at model scale and full scale is addressed. The formulation and development of an extrapolation method for a multi-component podded propulsor is described: model measurements are extrapolated to full scale using dedicated CFD computations. Finally, conclusions on the CFD-aided model test experiments are discussed.

1 MODEL SCALE EXPERIMENTS

As part of a more extensive research programme, MARIN conducted open water measurements on the Azipod® XL as commissioned by ABB.

1.1 Measurement setup

Model scale tests to measure the open water characteristics were carried out in MARIN’s Deep Water Towing Tank. Figure 3 and Figure 4 show the setup.

For the tests use was made of calibrated transducers for the following quantities: Carriage speed, unit forces and moments (6 dof), propeller torque, propeller thrust and the combined nozzle and post-swirl stator forces and moments (6 dof).

Propeller thrust and torque were measured with a conventional Q-T sensor which measured thrust and torque of the propeller blades including the hub. Afterwards, the thrust is corrected for the effect of the hub.

Within the hub of the propeller a 6-component frame of cylindrical shape was installed on which the stator blades were fitted. With this method, the combined forces and moments of the stator blades and the nozzle could be measured. The stator blades are 3D printed with high accuracy. For observation purposes, the remaining part of the nozzle was made on the lathe from plexiglass to obtain transparency.

Furthermore, the forces of the whole propulsion unit were measured in a 6-component frame connected to the pod shaft. The unit thrust is lower than the sum of the propeller thrust, stator and nozzle thrust due to the resistance of the pod housing.

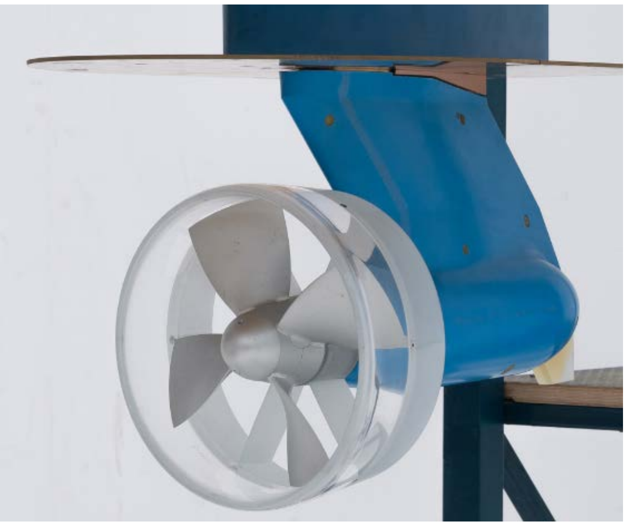


Figure 3: Photograph of the open water setup.

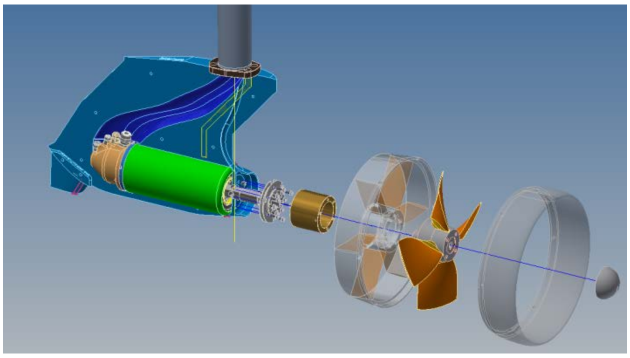


Figure 4: Measurement setup with electric drive, Q-T sensor with propeller shaft, 6-component sensor on which the 3D printed stator blades are mounted, propeller, transparent turned nozzle part and hub cap.

1.2 Open Water Measurement

At MARIN, open water characteristics are nowadays often determined by means of a Quasi Static Open water measurement technique (QSO) as presented by Dang et al. (2012) and Lafeber et al. (2013). Open water tests of propellers, pod units and thruster units traditionally were performed in a steady manner where the forward velocity and propeller rotation rate are constant during each measurement. In a QSO the forward velocity of the towing carriage is varied while the thrust and torque are measured continuously. With this method, the normal open water diagram (J=0 to Kt = 0) can be determined in one single run through the towing tank instead of multiple runs. This procedure greatly reduces the time required to perform open water model tests. There are hysteresis effects on the raw data, but those can be negated by taking the average of the accelerating and the decelerating parts of the measurement. Lafeber et al. (2013) show that there is a very good agreement between the results of the standard, steady procedure and of the QSO procedure.

Both methods have been applied to obtain the open water characteristics of the Azipod® XL. The differences between both methods were found to be less than 0.8% for the propeller and nozzle/stator forces and less than 1.6% for the unit forces. The largest deviations are found at bollard pull conditions. Typically, the accuracy of a conventional open water model test is +- 1% for other conditions. The QSO for an advanced propulsor with multiple components such as the Azipod® XL lies well within this band.

2 EXTRAPOLATION METHOD

Often several propulsion configurations are tested at model scale at MARIN. Podded propulsors are compared, with different shapes, wetted areas and appendages. The mutual comparison of extrapolated results should be as accurate as possible for a reliable prediction of the full scale performance. To that end, a best practice scale correction procedure has been applied.

2.1 History

Holtrop and Mennen (2003) describe the development of the current scale effect correction method as used at MARIN.

In the extrapolation of results of model experiments on complex propulsors, care is to be taken that the local velocity and the effects of the loading on the drag are taking into account. The magnitude of the local velocity is also influenced by the action of the propulsive elements of the propulsor. The drag of the passive components of the propulsors and their scale effect depends not only on the forward speed of the model, the scale factor, the shape and the area of the local wetted surface, but also on the propulsor-induced velocities. The latter are also subjected to scale effects because (1) the loading of the propulsor is a variable factor, to be determined by the experiment and, (2), the loading and the induced velocities depend on the wake of the hull and possibly also the scale effect correction on the wake.

Prior to the year 2000, the ‘50/50 rule’ was applied based on experience: ‘the scale effect is 50% of the model scale appendage drag, irrespective of its nature, scale and origin’. The POD-T as published by Holtrop (2001) and discussed in the ITTC (2002) showed its merits, but due to its difficulty, it was simplified into the current POD-U method.

At MARIN the POD-U method has been developed several years ago which takes into account the differences in the size and shape of the pod housing. The POD-U method predicts scale effect corrections for the full scale prediction. This POD-U method depends on the speed and loading of the propeller.

Hence, the simplified method POD-U was proposed with limited computational effort which can be used for the extrapolation of the model scale test results to full scale in order to obtain a reliable full scale speed-power prediction.

2.2 Analysis Model

This section described the principles of the POD-U method, which is simply based on actuator disk theory within a nozzle (Zondervan et al., 2006). The flow around the body is assumed to be characterized by a local flow velocity $\mathrm{V_{loc}}$ which is determined by a certain combination of the upstream velocity V and the propeller-induced flow $\mathrm{V_{ind}}$. The first contribution, the upstream velocity, is equal to the speed of advance $\mathrm{V_A}$, whereas the second contribution, the propeller induction, is approximated by:

$$\mathrm{V_{ind}} = \mathrm{V_A}\,\frac{1}{2\tau}\left(\sqrt{1+\tau \mathrm{C_T}} + 1 - 2\tau\right) \qquad (1)$$

which is based on actuator disk theory with a nozzle (e.g. Zondervan et al., 2006). The factor τ expresses the ratio of thrust over the propeller blades $\mathrm{T_p}$, and the thrust the nozzle and the stator blades $\mathrm{T_{ns}}$ as

$$\tau = \frac{\mathrm{T_p}}{\mathrm{T_p} + \mathrm{T_{ns}}} \qquad (2)$$

The flow around a thruster body is assumed to be characterized by a local flow velocity, $\mathrm{V_{loc}}$, which is determined as the sum of the upstream velocity $\mathrm{V_A}$ and a certain fraction, 2a, of the propeller induced velocity, $\mathrm{V_{ind}}$. The local velocity on a component of the pod unit can be described as

$$\begin{aligned} \mathrm{V_{loc}} &= 2\mathrm{aV_{ind}} + \mathrm{V_A} \\ &= \mathrm{aV_A}\frac{1}{\tau}\left(\sqrt{1+\tau \mathrm{C_T}} + 1 - 2\tau\right) + \mathrm{V_A} \end{aligned} \qquad (3)$$

where the factor a describes the relation between the induced velocity and the advance velocity where the induced velocity is predicted by Equation 1 based on actuator disk theory taking the advance velocity, thrust loading and thrust ratio between propeller and nozzle into account. Physically it gives the influence of the propeller wash on the resistance of the housing. It will be clear that when $\mathrm{a} = 0$ the propeller induction does not play any role in the local velocity and hence the drag of the pod housing.

The scale correction for frictional forces at model scale, $\Delta\mathrm{F}$, is simply based on the difference in friction coefficients at model scale and full scale

$$\Delta\mathrm{F} = \frac{1}{2}\rho_\mathrm{m}\mathrm{V}_{\mathrm{loc_m}}^2\left(\mathrm{C_{F_s}} - \mathrm{C_{F_m}}\right)\mathrm{S_h}\,(1+\mathrm{k}') \qquad (4)$$

where $\mathrm{C_{F_s}}$ and $\mathrm{C_{F_m}}$ are the friction coefficients at full scale and model scale respectively, $\mathrm{S_h}$ the wetted area and ρ_m is the model scale density. The form factor k' reflects the effects caused by the shape of the housing. It includes effects of local thrust deduction, increased frictional drag, flow separation and variations in the local flow conditions. The total scale correction is assumed to be the sum of the corrections for each component of the thruster

$$\Delta\mathrm{F_{tot}} = \sum\Delta\mathrm{F_{comp}} \qquad (5)$$

The standard ITTC scale corrections on the propeller thrust and torque have been applied.

2.3 Friction Line

In this work, the friction line as developed by Katsui et al. (2005) has been chosen for both model scale and full scale. This line is defined as:

$$C_F = C_F(\mathrm{Re}) = \frac{0.0066557}{(\log \mathrm{Re} - 4.3762)^{0.56725+0.042615 \log \mathrm{Re}}} \quad (6)$$

Where the Reynolds number should be taken as the local Reynolds number on each component based on its characteristic length and local velocity V_{loc}. A correction for the roughness on friction (full-scale only) is included as given by Prandtl-Schlichting's formula of roughened plates:

$$C_F = \left(1.89 + 1.62 \log \frac{L}{K}\right)^{-2.5} \quad (7)$$

with roughness k. This value is typically set to $K = 20$ µm for polished surfaces like propeller blades and stator blades. For the nozzle a value of $K = 40$ µm is chosen while the housing is somewhat rougher with $K = 50$ µm. This value was taken whenever it was greater than the Katsui friction line coefficient.

2.4 Application to the Azipod® XL

MARIN's in-house POD-U method assumes values for the factors a and $1 + k'$ based on experience and CFD calculations on typical pod configurations. POD-U, however, is based on conventional podded propulsors without nozzle and stator blades.

Hence, for a multi-component propulsor such as the Azipod® XL the POD-U methodology should be applied for each component of the propulsor separately. A dedicated CFD computation is required to predict the typical flow velocity and form factor of this component. For the Azipod® XL the strut, torpedo, fin, stator blades, propeller and nozzle have been considered as separate components.

For the Azipod XL, CFD is necessary to determine the contribution of the induced propeller velocity on the components of the pod. From this, as an engineering approach, the factor 2a can be determined to approximate the local velocity by means of actuator disk theory as given in Equation (3).

Note that computations with working propeller are required to determine the effect of the propeller wash over the components of the pod. An actuator disk approach or sliding mesh approach can both be used. These computations can be performed for open water conditions which is sufficient for the approximation of the local velocity.

3 RANS COMPUTATIONS

Figure 5 shows several views of the CFD ready (smooth and closed geometry suitable for meshing) and Azipod® XL geometry with the pod, the nozzle, stator blades and the propeller.

The Azipod® XL is simulated by unsteady Reynolds-Averaged Navier Stokes (RANS) approach with SST (Menter) k-ω turbulence model at full and model scales. The transient sliding mesh approach within commercial CFD code StarCCM+ version 10.06.009 is used. SST (Menter) k-ω has been applied as turbulence model. First, simulation results (propeller thrust, propeller torque, total thrust and total efficiency) are compared to experiments to learn how well CFD is able to predict XL performance at model scale. Then simulated results at full scale are used for the CFD-aided extrapolation method. From the simulations the volume mesh, pressure- and wall shear stresses on propeller and pod surfaces and velocity field are exported from the StarCCM+ and imported to third party software for further analysis to determine the form factors and local velocities on the pod components.

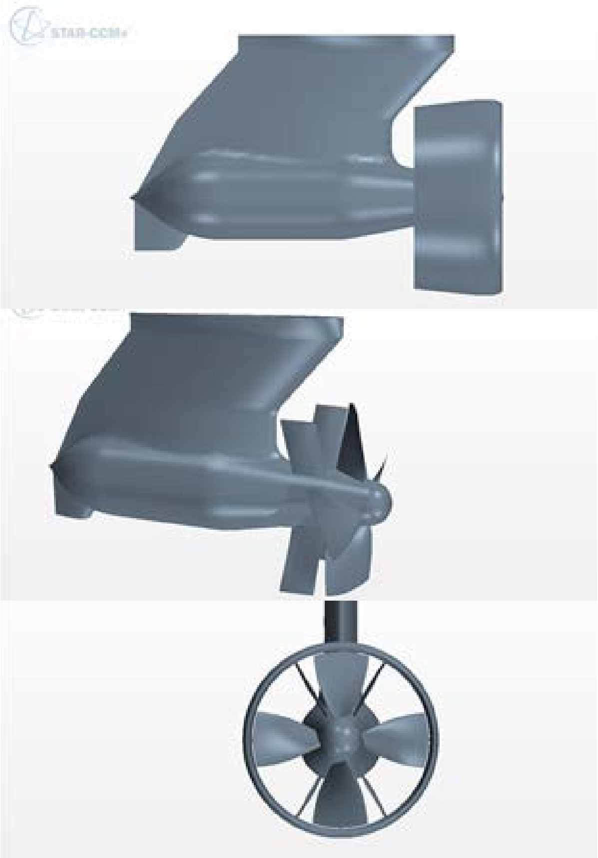


Figure 5: Views of the CFD ready Azipod® XL geometry

The simulation geometry is divided into rotating and stationary regions. The rotating region includes propeller blades, blade tips and hub and the stationary region includes fin, strut, nozzle, stator blades and torpedo together with inlet, outlet and sides surfaces of the simulation domain. The inlet surface is described as velocity inlet, the outlet surface as pressure outlet and side surfaces are defined as symmetry planes. The simulation domain is a rectangular box and it extends 10 propeller diameters upstream from the nozzle and 10 propeller diameters downstream from the torpedo. In the vertical direction, the simulation domain exceeds 10 propeller diameters above the strut and below the nozzle and in the lateral direction 10 propeller diameters from the nozzle.

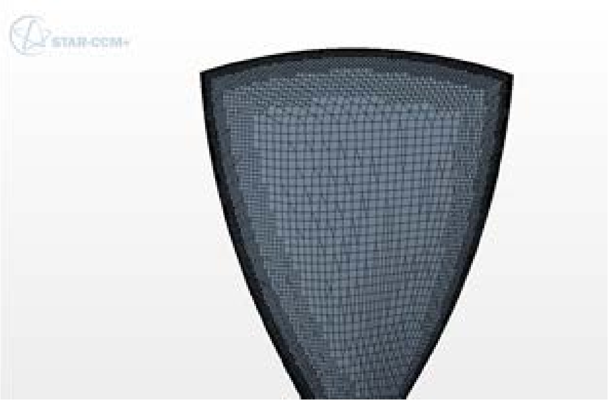


Figure 6: Mesh resolution on the propeller surface

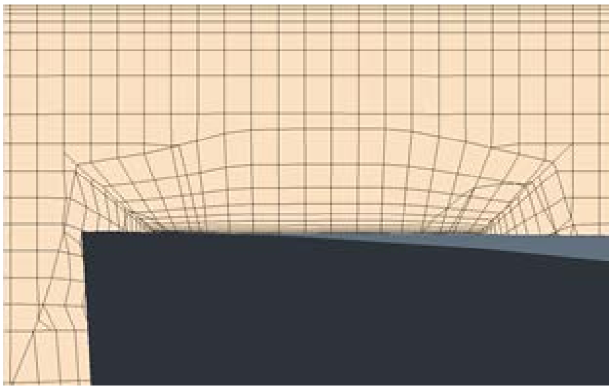


Figure 7 Mesh resolution on the gap between the nozzle and propeller blade tips. Mesh is shown on the plane of the propeller axis.

The rotating and stationary regions are meshed with trimmer cells and prism layers. The all-y^+ wall treatment is applied which is suitable for both wall-function-type and for low y^+ approaches. The mesh was generated at full scale and the resulting volume mesh was scaled for model scale simulations. The total number of cells is 21 million and the same mesh was used at all simulated inflow velocities. Second-order discretization schemes were used for mass, momentum and turbulent equations. Propeller diameter is D = 5.3 m at full scale and 0.23 m at model scale. As the sliding mesh approach is used, the time step size was set to 1 degree/time step. At an advance number of 1.1, the average wall distance is $y^+ = 97$ at full scale and $y^+ = 2.1$ at model scale. Figure 6 and Figure 7 show mesh resolutions on the propeller surface and on the gap between the nozzle and propeller blade tips.

4 RESULTS AND DISCUSSION

4.1 CFD results

Simulated open water performance for the propeller, nozzle and the pod unit is plotted in Figure 8 and Figure 9 at full and model scales, respectively. Figure 10 shows the comparison between full and model scale CFD results.

Axial velocity scaled by incoming undisturbed velocity at the propeller axis plane and at the plane downstream of the pod at full and model scales are presented in Figure 11 and Figure 12. In Figure 13, dimensionless pressure distribution (static pressure scaled by $0.5\rho n^2 D^2$) is plotted on the surfaces of Azipod® XL podded propulsor at full and model scales. In general, velocity and pressure distributions are pretty similar at both scales. However, in more detail, at model scale the velocity is smaller downstream of the propulsor due to the larger dimensionless resistances of the strut and the torpedo.

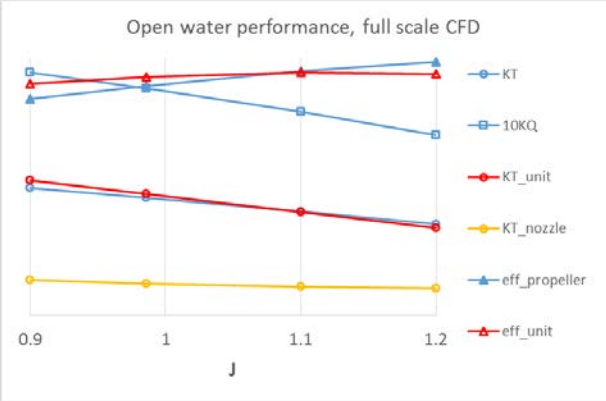


Figure 8: Simulated open water performance for the propeller, nozzle and the pod unit at full scale.

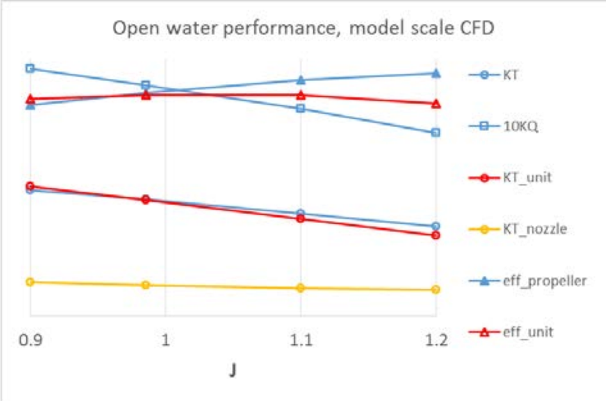


Figure 9: Simulated open water performance for the propeller, nozzle and the pod unit at model scale.

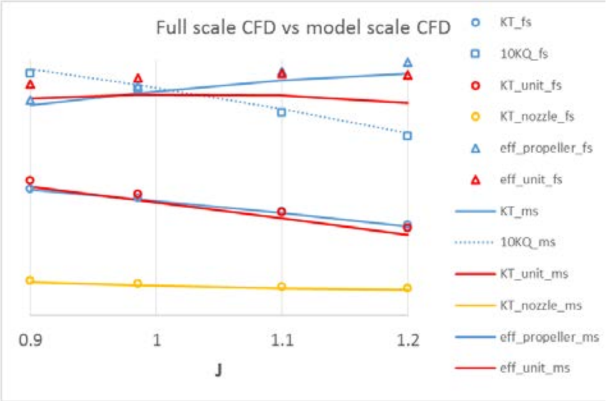
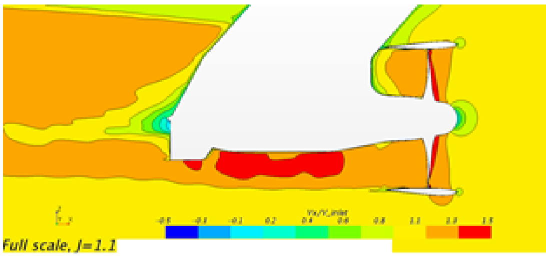


Figure 10: Comparison between full and model scale CFD. Symbols are CFD results at full scale.



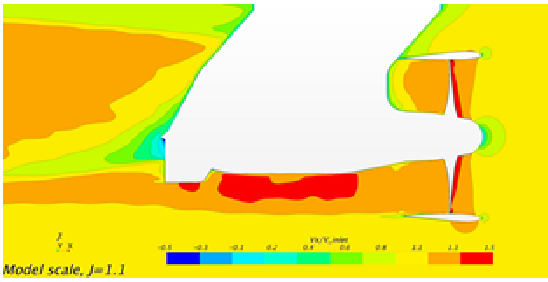


Figure 11: Scaled axial velocities at the propeller axis plane at full (above) and model (below) scales.

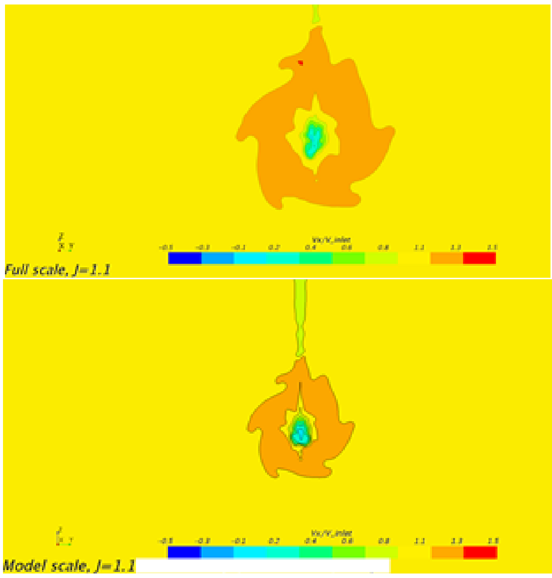
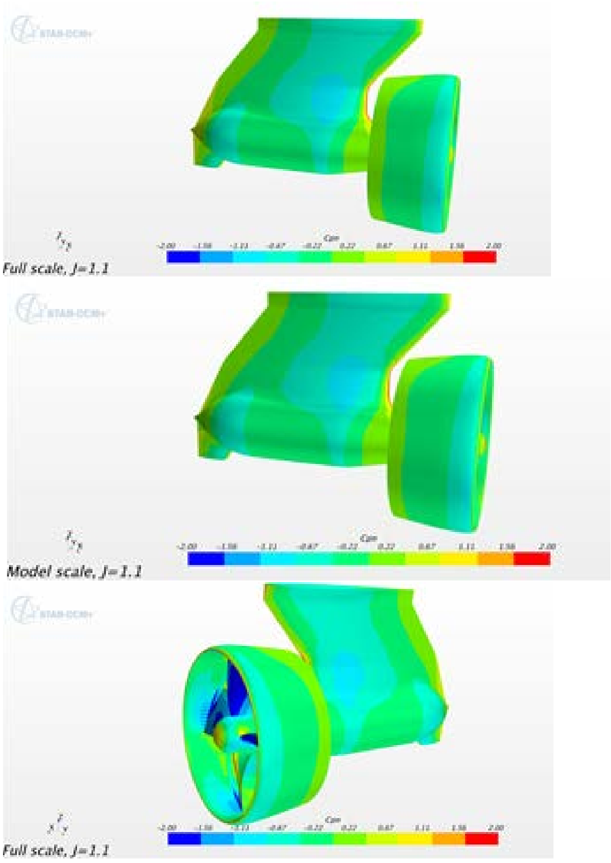


Figure 12: Scaled axial velocities at the plane downstream of the pod at full (above) and model (below) scales.



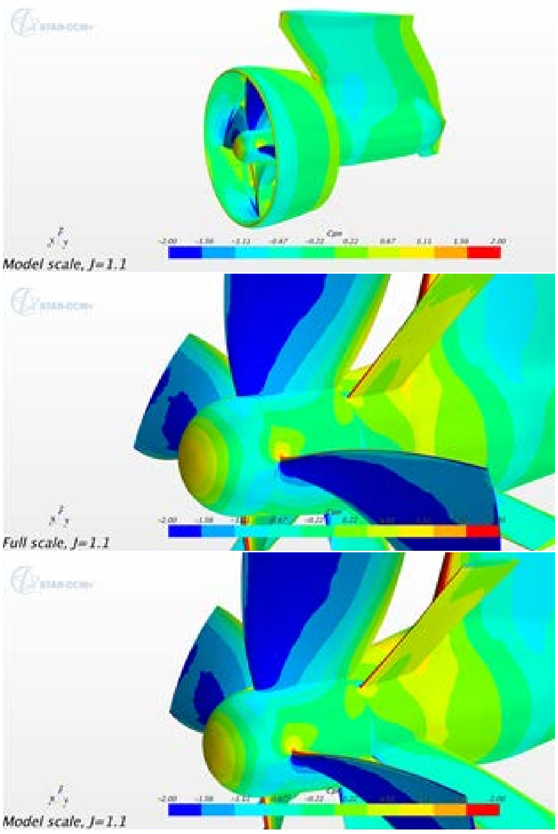


Figure 13: Pressure distribution on the surfaces of Azipod® XL podded propulsor at full and model scales.

4.2 Local Velocity

To determine the local velocity on a component, a number of streamlines just outside the boundary layer are defined within the CFD results. Note that the resulting local velocity is an approximate average value, since the velocity on a component fluctuates both in time and space. Model scale and full scale results at different J values give similar results, which gives confidence in the assumption that the value of ‘a’ in Equation (3) to determine the local velocity can be taken as a constant. The CFD prediction for the average local velocity Vloc of the part of the thruster together with the advance speed Va determine the factor a using Equation 3” and these CFD computations do not show disturbing flow separation at model scale for which the results should be corrected.

The outer surface of the nozzle and the inner surface yield an average velocity increase of 4.1% and 16.9% compared to the undisturbed inflow respectively. This yields for the outer surface $2a = 0.2$ and for the inner surface $2a = 0.9$.

Similarly for the stator blades, the average over a number of blades at different positions at both sides of the stator blades is chosen as the representative velocity. As Figure 14 shows, the local velocity varies significantly in space, and varies in time as well since it is a function of the propeller blade passage. Within this simplified extrapolation approach, the velocity is averaged which yields $2a = 1.3$.

Finally, the procedure is repeated for the torpedo and strut which yields on average $2a = 1.2$ for the torpedo and $2a = 1.4$ respectively.

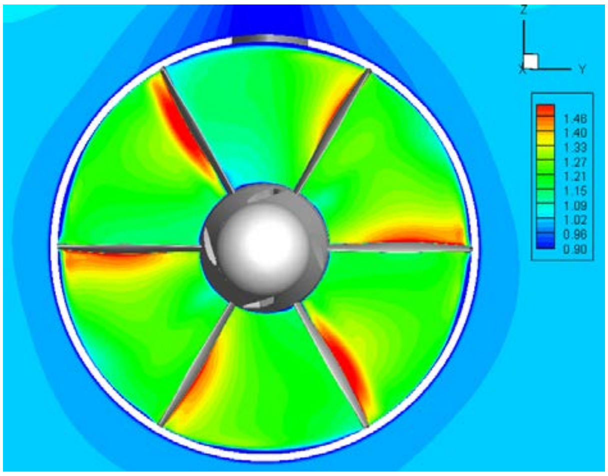


Figure 14: Scaled axial velocities around the stator blades

4.3 Form Factor

In addition to the local velocity, also the form factors are estimated. Table 1 below gives an overview for the available CFD computations. The pressure field from the propeller highly disturbs the determination of the form factor for CFD with propeller. As seen, for stator and strut the form factor is higher for the case with propeller. For the stator, the computations with propeller did not yield reasonable form factors. Moreover, the nozzle produces thrust, both in the computation with and without propeller, which counteracts the correct determination of the form factor. Hence, a form factor is estimated based on MARIN experience.

The form factor of the torpedo is rather high, indicating that the drag due to pure friction is rather low compared to its total drag. The total drag originates from the sum of the pure friction drag and pressure related drag which is influenced by the shape of the body, the effect of the viscous, unsteady flow on the pressure and the consequential flow separation (or imperfect pressure recovery), see Figure 11, behind the body.

Table 1: Determination of the form factors

Form Factors (1+k’)	Nozzle	Torpedo	Strut	Stator
FS J = 1.1 CFD No Prop	-	2.59	1.58	1.83
FS J = 1.1 CFD Prop	-	2.66	2.35	-
FS J = 0.9 CFD Prop	-	2.72	2.61	-
FS J = 1.1 Friction Line	-	2.57	1.66	1.49
MS J = 1.1 CFD No Prop	-	2.47	1.68	2.70
MS J = 1.1 CFD Prop	-	2.62	2.04	-
MS J = 0.9 CFD Prop	-	2.61	2.13	-
MS J = 1.1 Friction Line	-	2.16	1.55	1.15
Choice for further extrapolation	1.2	2.5	1.6	1.3

The form factors are determined with:

$$(1 + k') = \frac{F_v}{F_{tot}} \qquad (8)$$

where F_v is either the viscous force from CFD or an estimate based on the friction line as given in Equation (6).$F_{tot}$is the total force (pressure and viscous contribution) on the component.

4.4 Extrapolation results

Based on the local velocity and form factors, the wetted area, roughness and characteristic length, the extrapolation of the model scale experiments has been performed.

Figure 15 shows the comparison of the open water characteristics between the model scale experiment results and the extrapolated full scale performance based on the methodology as described in this paper. The following can be observed:

- The scale effect on the thrust of the total unit is 10% around J = 1.1 which is significantly more than a conventional propulsor which features a scale effect of 4 to 6%.
- The nozzle / stator combination produces thrust over the whole operational range.
- Relatively, the nozzle and stator blades feature the highest scale effect, especially at higher advance ratios.

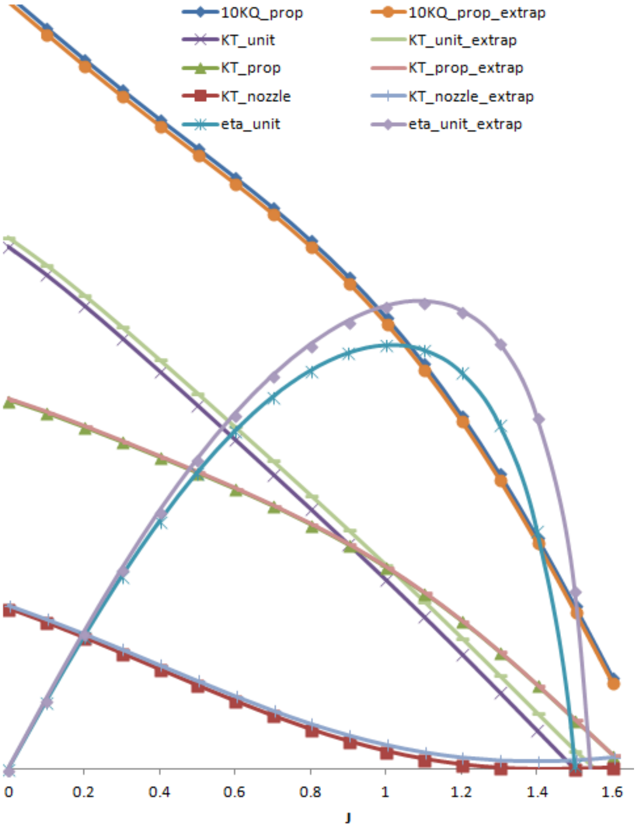


Figure 15: Comparison between measured and extrapolated open water characteristics.

Figure 16 shows the comparison between:

1. **Measured** efficiency at model scale, similar as what is presented in Figure 15.
2. Extrapolated efficiency according to the standard **POD-U** method. This comparison shows that the standard POD-U method does not suffice for a multi-component pod such as the Azipod® XL. The standard POD-U considers the Azipod® XL as a conventional propulsor as if the nozzle and stator were not present. The scale effects on the nozzle and stator blades should explicitly be taken into account for a reliable extrapolation towards the full scale performance. The scale effect for a complex propulsor such as the Azipod® XL, is relatively large compared to a normal podded propulsor.
3. Extrapolated efficiency according to the **CFD aided** method as presented in this paper. This method captures the CFD predicted difference between full scale and model scale reasonably well. Hence, this method is advised for any complex propulsor such as the Azipod® XL.
4. Extrapolated efficiency **based** on **CFD** by adding the difference between full scale and model scale CFD to the measured efficiency at model scale.
5. Full scale and model scale CFD results. In general, the CFD predicts 1.5 to 3.6% higher efficiency at model scale for the considered J values from 0.9 to 1.2. This tendency is also visible in the comparison between the CFD aided extrapolated results and the full scale CFD results.

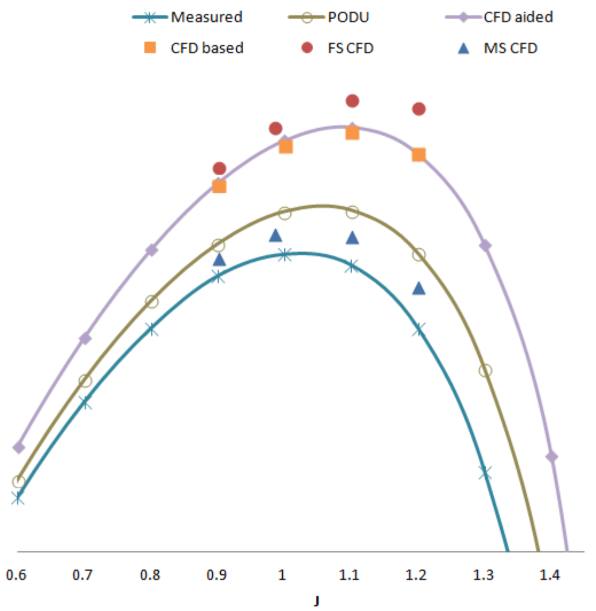


Figure 16: Comparison of the efficiency with different methods at different scale.

5 CONCLUSIONS

The following summarizes this paper:

- The combination of model experiments and CFD calculations in model and full scale are needed to understand more deeply the performance of a multi- component propulsion device such as the Azipod® XL.
- A new scaling procedure has been developed for Azipod® XL pod unit which considers scaling characteristics of each individual component of the propulsor.
- The scale effect on the Azipod® XL is relatively large compared to a conventional unit without nozzle and stator blades.

For a reliable prediction of full scale performance of a complex multi-component propulsor, it is recommended to perform CFD computations on at least two conditions at model scale and full scale with and without propeller action in addition to model scale measurements.

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