Concept investigation and development for Azipod® equipped with linear flow propulsor

During 2016, ABB introduced a new member to the well-known Azipod® X-series. The main difference between the older XO and the new XL is the concept of how thrust is generated.

ANDREI KORSSTRÖM
Product Manager
andrei.korsstrom@fi.abb.com

PASI MIETTINEN
Senior CFD Analyst,
PG Propulsion Solutions
pasi.miettinen@fi.abb.com

TOMI VEIKONHEIMO
Senior Principal Engineer,
PG Propulsion Solutions
tomi.veikonheimo@fi.abb.com

VELI-PEKKA PELJO
Senior R&D Project Manager,
PG Propulsion Solutions
veli-pekka.peljo@fi.abb.com

The functional concept of the new XL is based on a pump-jet functionality. The following paper will describe how the concept was developed within ABB, and how the functionality was verified with the help of model tests and CFD (Computational Fluid Dynamics). Based on the results, the body form was further developed to give the optimum performance. At the same time the strength was investigated using FEM (Finite Element Method) calculations derived with the CFD results as an input to give the best possible model of the actual operational condition.

Introduction
Looking at the development with the existing pod propulsion concept, the conclusion was that there are only limited improvements that can be developed for the existing pod configuration. In response to this, ABB started a new research program in 2014 to investigate new propulsion concepts and see if there were some benefits that could be developed into new propulsion concepts. One of the concepts was the linear jet propulsion concept that will be further discussed in this paper.

Background and concept
The basic concept of linear flow propulsion is to have a duct that accelerates the flow to the rotor. The rotor on the other hand can be more loaded in the top region, and additionally works in the accelerated axial inflow from the duct. After the rotor, the stator blades straighten the flow and make use of the rotational flow that would otherwise be lost to the flow.

The arrangement can be either with the stator blades in front or behind the rotor, depending on how the overall configuration is set up. For instance in naval applications, where the system has been researched and implemented since the 1960s, the concept is traditionally used as a pushing configuration (torpedo and submarine propulsion), which means that the stator blades are located in front of the rotor.

Basic study
The first assessments for the concept were done by the Krylov State Research Centre (Krylov) on behalf of ABB. The first estimation was for a 17.5 MW device envisaged to operate on a vessel with a design speed of 25 knots. The basic design was done for open water conditions, where the wake field was only considered as an axial component. However, the first estimation was to decide on either a pulling or a pushing version of the concept. The difference in structure was that with a pulling configuration the rotor would be located before the stators, whereas for the pushing they would be the other way around.

The first estimations were for a rotor alone with a nozzle. To this a set of stator blades were added in the calculations, where the aim was to have no swirl after the last component. These concepts were then calculated at different revolution rates and rotor diameters, where the variable factor was the pitch for the rotor (example shown in Figure 1). The outcome of the optimisation routine was that the pulling option showed a couple of percentage points better performance than the pushing option. Additionally, an investigation on the effect of the blade area ratio was investigated for the two concepts. This was based on the risk of cavitation inception. The basic concept was that both options should fulfil the required margin against cavitation inception. With the computational comparison, the conclusion was that the pushing type would also require a higher blade area ratio to match the same cavitation inception criteria.

The optimum nozzle dimensions were selected based on Krylov's experience with nozzle designs. They have developed a formulation based on model tests series where the nozzle dimensions are variables of overall diameter and the cross sectional diameters of the hub at different locations in the nozzle.

Based on the basic study, ABB opted for a pulling version of the concept with an optimised rotor and nozzle configuration, even if that would increase the challenges of handling overall forces and moments at the mounting block of the unit. The selection was made purely from a hydrodynamic aspect.

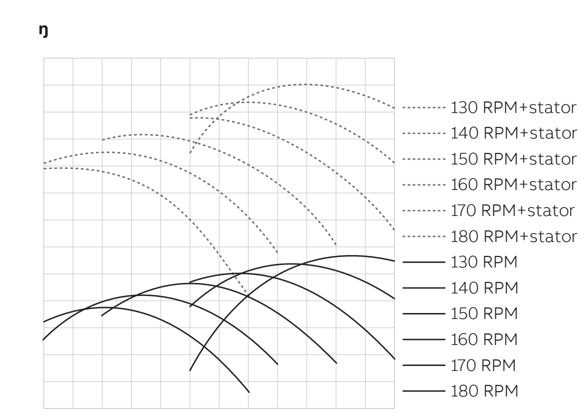

Figure 1: Example of diameter optimisation

A 3D model of the pod body was delivered by ABB to Krylov, who performed the first CFD (Computational Fluid Dynamics) calculations in full scale for the concept to verify the estimated performance. Based on the calculations the pitch was slightly low, but was corrected before the model tests were conducted, also at the Krylov facility.

The conclusion of the first CFD calculations showed that the estimated efficiency in full scale would be approximately 0.72. Based on the model tests, the estimation at the time was that the efficiency in full scale was 0.71, or basically in line with the CFD calculation, given that at the time there was no scaling method for the concept. At the time, scaling was done according to Krylov's earlier experience with pod propulsion, i.e. the propulsion components (rotor, nozzle and stator blades) were assumed to have the same proportional drag in full scale as in model scale. However, the pod body was assumed to have 30 % less proportional drag in full scale. As regards the cavitation test, gap cavitation was only present up until the design advance value, after which some pressure cavitation was present.

Optimisation and verification
Concluding from the base case, the following issues could be improved in the first optimisation round. The pod body was to be optimised for the new propulsion concept. In the first round the body was more or less a copy of the currently used body form for the Azipod® XO series. When the nozzle was introduced at the front of the pod, the effect on the steering forces was quite significant, hence the steering axis had to be shifted forward for the whole pod. (Due to the length of the nozzle the shaft line had to be lengthened). In addition, the indication from the first design study was that the gap between the pod strut and the nozzle should be larger. This contradicts the need to shift the steering axis forward, so the pod body for the upper part had to be an optimisation with these two boundaries in mind. To gain the optimum balance for the steering forces, a small fin was also introduced at the end of the torpedo, to give a balancing force at higher steering angles. Additionally, due to the longer shaft line the torpedo body could be slimmer compared to the current version. However, significant importance had to be assigned for the overall rotational radius of the pod not to grow too large.

Since the pod body was provided by ABB, it meant that the next step in the optimisation of the body was solely up to ABB. Hence the decision was made to switch the verification of the optimised pod to Marin instead of Krylov. The main reason for this was to get a third party involved, and to develop a scaling method for the new concept. In the meantime Krylov continued work on a numerical optimisation routine for the multiple component system, consisting of the passive and active parts attached to the pod housing.

To develop the new pod body, ABB used in-house CFD and FEM calculations to derive the optimised form that would later be used in the upcoming model test. The calculations were utilised by employing the results from the CFD calculations as input for the FEM calculations. The different operational scenarios included stationary forward operation as well as oblique operation at various vessel speeds. The modifications in the hull structure that were studied were the azimuth axis location, slanted strut design, fin location, correlation between stator and rotor blade number and nozzle-rotor location.
Such results, as shown in Figure 2, were used to validate the design from a strength point of view, in different operational conditions. Similarly, over all force distributions, such as the steering force and total resultant force diagrams, were used to analyse the acting forces depending on operational conditions.

Numerical optimisation routine for the propulsor
Simultaneous to the development work going on at ABB on the pod body, Krylov continued to develop their design process for the nozzle, rotor and stator combination. This has been described in more detail in Marinich, Yakolev, Ovchinnikov& Veinkonheimo 2017, but in short the process is as follows: The main routine is to use a BEM (Boundary Element Method) to calculate the flow around each component in the propulsor, i.e. nozzle, rotor and stator. However, the flow over the nozzle will depend on the loading on the rotor, which again will affect the flow over the rotor and stator blades, so the routine is a multi-iterative process to reach the converged solution for the operational point in question. With the calculation routine set up, the next step is how to proceed with the actual optimisation routine for the different components. Starting from the rotor, the goal is to achieve as much efficiency as possible, but without risking the strength or exceeding the cavitation criteria (where off-design conditions can be included) and still not exceeding the main boundary of the torque in that operational condition. The stator blades are optimised with a similar routine as for the rotor, with the difference that the main boundary is not the torque generated by the motor, but that the vorticity after the blades should be minimised. Additionally, the strength criteria are higher for the stator blades as they are the main supports for the nozzle construction. For the optimisation, the nozzle is separated into three different surfaces: the outer surface, the inner surface before the rotor, and the inner surface after the rotor. The aim in nozzle optimisation is to uphold the flow rate, see that the transition between the surfaces is smooth, and eliminate separation.

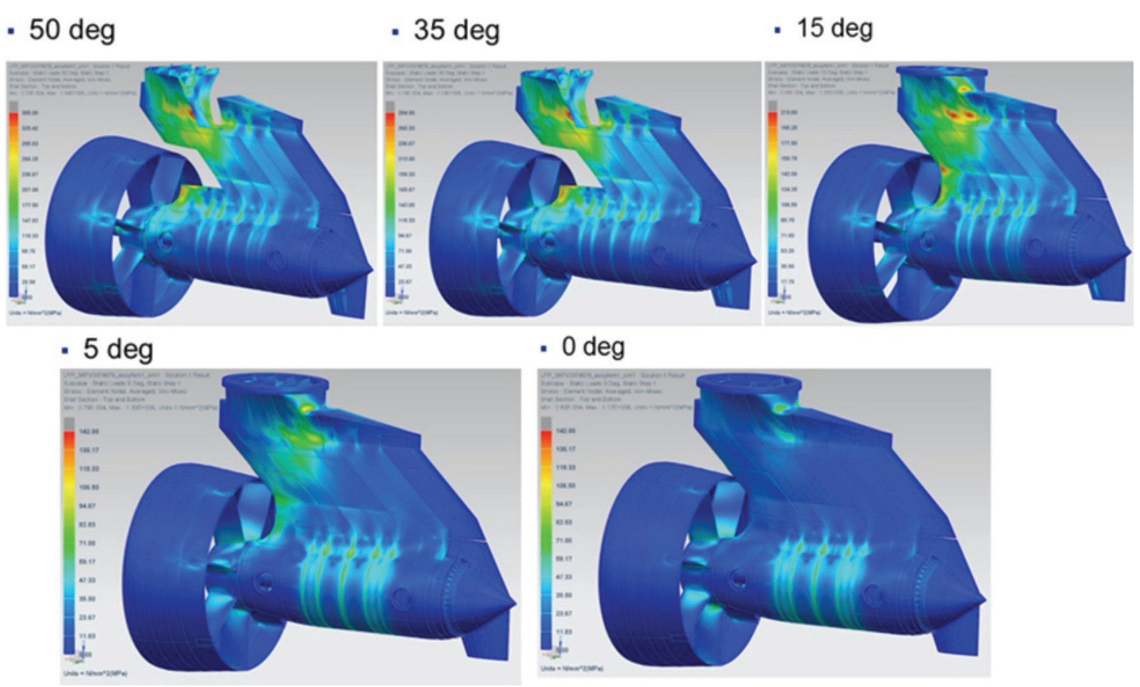

Figure 2: Results of oblique flow FEM calculations

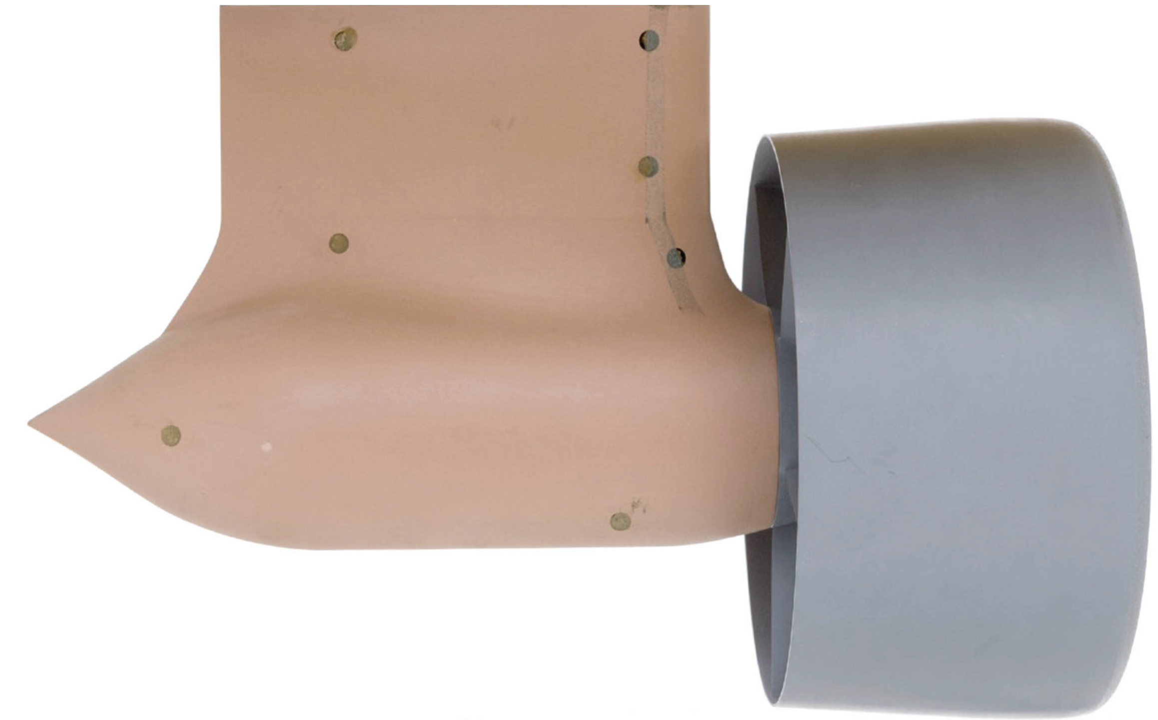

Figure: 3 Initially tested model propulsor

Following the optimisation routine a case study was done at Krylov. The propulsion configuration was analysed with CFD calculations, where special attention was given to the pressure distribution over the nozzle, pressure distribution on the blades during one rotation (no pressure spikes), average flow speeds before and after the stator blades, and additionally some off-design conditions to see that the system will work in these conditions as well. Based on the CFD for the basic study, the achieved efficiency was 72%, after the optimisation routine the achieved efficiency in the CFD calculation was 75%, and in model scale test 69%. The difference between the CFD and model tests is due to the scale effect in the system.

Scaling
As mentioned earlier, the verification tests for the new concept were done at Marin in the Netherlands. One significant issue realised early in the process, was that the current scaling method POD-U would probably not be sufficient for the new multi component concept. So in a collaboration between Marin and ABB, a new scaling methodology was developed which has been presented in Veikonheimo, Miettinen & Huisman 2017, but will be shortly described below: The assumption is that the model test values should be corrected for the Reynolds scale effect. The rotor is corrected for the thrust and torque according to the ITTC '78 correction method, but for the passively working components there is no clear methodology. The PODU-U method developed by Marin corrects the resistance of the pod housing based on the local Reynolds number, where form factors and velocity profiles are derived for the

"conventional" pod form. However, in this case we have components such as the nozzle and the stator blades for which there were no derived form factors or velocity profiles. So, in a collaboration where ABB did the CFD calculations, both in model and full scale, and Marin did the model tests, the same methodology as used in the POD-U method was further developed for scaling of multi component propulsors. Based on the CFD calculations, Marin devised form factors and velocity profiles for the stators, pod body, and nozzle. There was some inconsistency regarding the nozzle, so Marin used their experience to derive some suitable values. Additionally, the Katsui friction line was used both for model and full scale, but in full scale cases where the Katsui friction line was exceeded by the Prandtl-Schlichting's formula for roughened plates, the larger value was used.

The development showed that for a multi component propulsor, such a complex scaling method is needed, as the POD-U method did not sufficiently catch the relatively large scale effect compared to a conventional pod.

Verification

In order to verify that the results achieved at Krylov and Marin would be the same, the exact same geometry was tested at both facilities. (Both facilities manufactured their own models but according to the same specification).
At 15 Hz, the maximum efficiency in model scale varied by 3.5%, so there was clearly some discrepancy between the different basins. Thus it was necessary to do the verifications at two different, well renowned basins to verify the new concept. Similar differences between model basins have been noted earlier with "conventional" pod housing (internal, non-public report from 2006), which only underscores the importance from a pod manufacturer's point of view to develop a reliable scaling method for podded propulsion.

Adapting the scaling method described above to the model results measured at Marin and comparing them to the CFD results from Krylov, the difference in maximum efficiency was down to approximately 2%, which indicates that the prediction from two different model basins are within reasonable correlation of each other.

The current concept design was done solely for open water, i.e. no tangential or radial wake component had been taken into account in the design phase of the rotor-stator-nozzle configuration. However, based on the results from the open water test, the performance results were suitably in line with a project under construction with ABB Azipod® propulsion. In collaboration with the shipyard, ABB ordered a model test series from Marin consisting of self-propulsion and cavitation tests, to be compared to the performance of the current configuration. Based on the self-propulsion test results, the vessel speed gain was 0.33 knots at the design power rating, corresponding to the a hO value for the propulsor of 0.73 under the vessel. Given that this is a non-optimised system for the current project, it serves only to indicate the minimum achievable benefits of such a system.

In the cavitation tests, some suction side cavitation was present, which was expected, as the rotor was not designed with the correct wake field. In a design project it is assumed that the rotor can be designed without sheet cavitation. More challenging will be to cope with the gap between the nozzle and the rotor. During the cavitation test, pressure pulses were also measured on the hull in the same locations as for the "conventional" pod propulsion. Based on measurement results, the propeller induced pressure pulses were approximately 50% of that measured with a "conventional" pod propeller. The same value also translated to 50% of the FZeg (criteria). Part of the difference comes from the fact that the rotor diameter was smaller than the propeller diameter, so the distance to the hull was slightly larger. Additionally, the nozzle also gives an advantage for the new arrangement, especially since there was some suction side cavitation present on the rotor, whereas there was close to no cavitation present on the propeller.

Summary and conclusions

This paper has described in brief the development process that has been used to develop a new concept for pod propulsion. The development included numerical optimisation routines as well as new scaling methods for multi component propulsors, on top of the conventional development work.

Although considerable design work remains on cavitation inception, the hydrodynamic benefits with respect to efficiency and induced pressure pulses are clearly worth the effort.

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Figure 4: Azipod® XL