Application of Various Computational Methods to Predict the Performance and Cavitation of Ducted Propellers

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ABSTRACT
This paper presents results of various computational methods that were applied to ducted propellers. It includes results of the VLM MPUF-3A, the BEM PROCAL and the CFD package Star-CCM+. The results are compared with each other and with experiments. The paper also presents highlights of a sensitivity study of PROCAL. The RANS results are generally in good agreement with the experiments. Given their limitations the VLM and BEM also show a good agreement with experiments and RANS.

Keywords
Ducted propellers, CFD, BEM, VLM, Cavitation.

1 INTRODUCTION
During the past decades the methods for design and analysis of open propellers have steadily evolved. In the 1970ies the first vortex lattice methods (VLM) were developed, followed by boundary element methods (BEM) and more recently Reynolds- averaged Navier Stokes (RANS) simulations. At Wärtsilä VLM and BEM are used extensively in the daily design practice of open propellers in steady, unsteady, wetted and cavitating conditions. RANS (Star-CCM+) is also used on a daily base for steady problems, and more and more RANS is also applied to unsteady and cavitating problems.

The development of methods for ducted propellers is however much delayed. Until recently there were no accurate and efficient tools for the analysis of ducted propellers. During the past decade RANS has proven to be an accurate method for the prediction of the performance of ducted propellers. The relative long computational time of these calculations (not to mention the time that is required for meshing and post processing) however justifies the development of more quick but obviously less accurate tools based on VLM or BEM.

Recently such methods became available. The VLM MPUF-3A that has been developed by Prof. Kinnas and his team at UT now has reached maturity for the application to ducted propellers. Also the BEMs PROPCAV (also developed by UT) and PROCAL (developed by MARIN) show promising results for ducted propellers. Questions like How to handle the ship’s wake for ducted propellers? however still remain.

This paper will present results of MPUF-3A, PROCAL and Star-CCM+ (RANS). First the various methods will be described briefly. Then their results will be compared with each other and with experiments. The results comprise open water characteristics, pressure distributions on the propeller blades and the duct and also some cavitation patterns. The paper also highlight some results of the extensive sensitivity studies that were conducted. Finally conclusions are drawn on the accuracy and computational efficiency of the various methods.

2 VARIOUS COMPUTATIONAL METHODS
This section briefly describes the various methods that were used.

2.1 MPUF-3A
MPUF-3A is a Vortex Lattice Method (VLM). The development started in the 1970ies at MIT by Prof. Kerwin - see for instance Kerwin and Lee (1978). Later the development continued at the University of Texas at Austin under supervision of Prof. Kinnas. It was here that all developments related to ducted propellers were done.

MPUF-3A does not solve the flow around the duct itself. It is coupled to another code that solves the flow around the duct. Several methods have been applied: an Euler solver named GBFLOW (Kinnas et al., 2005), a Boundary Element Method and a RANS solver (Kinnas et al., 2012). In the Euler or RANS code the propeller action is represented by body forces. In MPUF-3A the duct effects are taken into account through the inflow and through an image of the blade singularities in the duct surface.

Figure 1 shows the coupling procedure between MPUF-3A and RANS. First an MPUF-3A calculation is made. Then the coupling code PF2NS (Potential Flow to Navier Stokes)
is used to compute the body forces for the RANS calculations. Subsequently the flow around the duct is solved. Then PF2NS calculates the effective wake by subtracting the propeller induced flow (follows from MPUF-3A) from the total velocity field that was calculated by RANS. There are several options for calculating this effective wake: at a flat upstream plane that is perpendicular to the propeller shaft (option 1), at a curved surface that is located slightly upstream of the swept leading edge contour of the blade (option 3), and at the control points on the propeller blade (option 5). This paper shows results of the latter two options.

2.3 Star-CCM+

Star-CCM+ is the standard CFD package at Wärtsilä. It is used extensively in day to day propeller design and for various consultancy tasks. The Reynolds-averaged Navier-Stokes (RANS) equations for fluid flow are solved on a computational domain surrounding the propeller-duct-shaft system. The two-equation SST k-ω model was selected as the turbulence model.

Nowadays at the Wärtsilä CFD department, a methodology is developed to perform open water calculations for (ducted) propellers, (ducted) propeller rudder combinations and thruster units (Bijlard and Bulten, 2015). In order to apply the same methodology for all different cases, the full propeller and duct are modeled instead of only 1 blade.

The fluid domain is modeled as a cylinder centered around the shaft of the propeller, see Figure 2. The mesh is predominately structured hexahedral with an extrusion layer near the surfaces. At the intersection of the extrusion layer and the structured background mesh, the cells are trimmed to polyhedrals. The height of the first extrusion layer is chosen such that the y+ value is smaller than one. Cross-sections of the mesh in the axial and radial directions are given in Figure 3. The size of the numerical domain and position relative to the propeller are sufficiently large for the solution to become independent. The mesh consists of approx. 6M cells.

Figure 1: Coupling process between MPUF-3A and RANS

The steady MPUF-3A results that are shown in Section 5 follow from MPUF-3A - Fluent interaction calculations that were carried out by the team of Professor Kinnas at the University of Texas at Austin.

2.2 PROCAL

PROCAL is a potential based Boundary Element Method (BEM) that was developed by the MARIN CRS consortium. During recent years the MARIN CRS PRODUCT working group extended the code to make it suitable for ducted propellers. The formulation generally follows the method of Baltazar et al. (2012). Contrary to MPUF-3A this method solves the flow around the propeller and duct at once. The code includes a model for the leakage flow through the gap between the blade and the duct and an alignment procedure for the propeller blade wake. A special feature of the wake alignment procedure is that it takes the effect of the boundary layer on the duct surface into account.

Figure 2: Graphical representation of the boundary conditions

At the inlet of the cylinder the velocity is prescribed and at the outlet the pressure. For a thrust producing operating condition of the propeller, the fluid through the duct is accelerated. As a result, a vena contra occurs. To enable the fluid to contract, an extrapolated pressure boundary is assigned to the cylindrical surface of the mesh. The
The rotational velocity of the propeller is imposed by a moving reference frame applied to the inner region of the domain, see Figure 3. The tangential velocity at the duct surface is fixed to zero with respect to the stationary frame. The rotational velocity of the shaft and hub cap outside of this inner region is imposed by a tangential velocity vector on the walls, relative to the rotational axis of the propeller.

The Star-CCM+ results that are presented in Section 5 were made by Wärtsilä commissioned by the MARIN CRS PRODUCT working group.

3 VALIDATION CASES
This section briefly describes the cases that are used in this paper. The first two are standard series propellers. They are used in the sensitivity analyses (Section 4) and the open water validation study (Section 5). The third is used for the validation of the unsteady cavitation results of MPUF-3A (Section 6).

3.1 Ka 4-70 propeller in 19A duct
The Ka 4-70 propeller comes from the famous Wageningen propeller series. It is a traditional ducted propeller that has a large chord at the tip. For all results in this paper the Ka 4-70 propeller with a P/D ratio of 1.0 is used and it is operating in the MARIN 19A duct. The geometries of the Ka 4-70 propeller and 19A duct are reported in Kuiper (1992).

Recently the MARIN CRS PRODUCT working group carried out new model experiments for this propeller duct combination. During these experiments pressures were measured on the duct surface, in addition to the regular open water characteristics. Furthermore the wake of the propeller was measured in a number of planes by means of PIV and cavitation observations were done in MARIN’s Depressurized Wave Basin, but these results do not appear in this paper. For these new tests new propeller and duct models were manufactured. The hub-diameter ratio of this new propeller is slightly larger than the original propeller.

3.2 D 4-70 propeller in 19A duct
The D 4-70 propeller is a series propeller of more modern design. It was designed and tested in the CD-Series JIP. This Joint Industry Project aimed at an extension of the famous Wageningen propeller series (B-Series and Ka series). The C-series is a series of open controllable pitch propellers (CPPs) and the D-series is a series of ducted CPPs. The propellers are designed to reflect today’s propellers. The propeller thrust and torque and the duct thrust were measured for a large range of pitch settings and for the full first and fourth quadrant. Please refer to Dang et al. (2013) for more information about the CD-Series.

Recently the MARIN CRS PRODUCT WG also carried out model experiments for one of the D 4-70 propellers in 19A duct. The scope was the same as for the Ka 4-70 propeller. The results of the CD-Series JIP are bound to confidentiality agreements that prohibit disclosure of the propeller geometry. The results can only be presented in a normalized way.

3.3 TSHD Uilenspiegel
In the CoCa (Correlation of Cavitation) project full scale observations, model experiments and calculations were done for the Trailing Suction Hopper Dredger Uilenspiegel (Ligtelijn et al., 2004). This ship is propelled by two CPPs that are operating in 19B ducts. The propulsion configuration is quite complicated as the ducts are partly integrated in a tunnel that guides the flow to the propellers (see Figure 4). In Section 6 MPUF-3A results are compared with the CoCa model experiments.
4 SENSITIVITY ANALYSIS
In the MARIN CRS PRODUCT working group Wärtsilä performed extensive sensitivity and validation studies with PROCAL for the D4-70 propeller in 19A duct. This section presents highlights of this sensitivity analysis. Because of confidentiality the axis scales of the charts in this section were removed. In most cases the chart origin is at the bottom left corner.

4.1 Wake alignment
Alignment of the vortex wake of the propeller blades appears to be very important for ducted propellers. Figure 5 shows the effect of wake alignment on the open water characteristics that PROCAL predicts. The thick red line follows from calculations where the wake was aligned with the flow for each advance ratio. The green line follows from calculations where the blade wake was taken according to the blade pitch (constant in downstream direction but varying with radius). The wake alignment clearly has a strong impact on the predicted propeller thrust and torque. The effect on the duct thrust is not that big.

The blue line follows from a calculation where the wake was aligned for an intermediate J. This wake geometry was also used for the other advance ratios. It is remarkable how well these results agree with the results of the calculations where the wake was aligned for each J. This is important as wake alignment is very computationally intensive. Furthermore wake alignment is not always very robust, particularly at low advance ratios (therefore no fully aligned results were obtained for very low J). It must be remarked that low advance (even up to bollard pull) is very relevant for ducted propellers.

![Figure 5: Effect of wake alignment on open water characteristics](image)

There is one other aspect of wake alignment that is worth mentioning. Following Baltazar et al. (2012) PROCAL takes the effect of the boundary layer on the duct into account in the wake alignment procedure. This causes a significant reduction of the pitch of the blade wake at the tip. This also reduces the propeller thrust and torque as shown in Figure 6. However, for this case (D4-70 propeller) this effect is much smaller than what was reported by Baltazar et al (2012) who used the Ka 4-70 case.

![Figure 6: Effect of including the duct BL in the wake alignment on the open water characteristics](image)

4.2 Gap flow
PROCAL is equipped with a simple transpiration model for the flow through the gap between the blade and the duct. In this model the flow through the gap panels is related to the square root of the pressure difference across the gap:

\[ Q = C_q \cdot h \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \]

where \( C_q \) is the empirical discharge coefficient, \( h \) is the height of the gap, \( \Delta p \) is the pressure difference across the gap and \( \rho \) is the fluid density.

Figure 7 shows the effect of gap transpiration on the predicted open water characteristics. It shows results for \( C_q = 0.0 \) (i.e. a closed gap) and for \( C_q = 0.6 \). The effect on the open water characteristics is only limited.

![Figure 7: Effect of gap transpiration on the open water characteristics](image)
Figure 8 shows the effect of gap transpiration on the span-wise distribution of loading (in this figure the axial component of the force per unit span is shown). It is more pronounced than the effect on the open water characteristics. As one may expect the main differences appear at the tip.

![Figure 8: Effect of gap transpiration on the span-wise distribution of loading (axial force)](image1)

Figure 9 shows the effect of gap transpiration on the pressure distribution at 0.95R radius for an intermediate advance ratio. C_{pn} is zero at the horizontal black line. There is a significant effect on the calculated pressures around 35% of the chord. One must realize however that, due to the blade shape of the D 4-70 propeller, the leading edge at the tip (1.0R) is actually very close to the 35% chord position at 0.95R. The effect of gap transpiration mainly manifests itself at the leading edge at the tip and the area around this location. The C_q value of 0.6 appears to result in a good correlation of the PROCAL pressure with the Star-CCM+ RANS results. At lower radii there is hardly an effect of gap transpiration on the predicted pressure distribution.

![Figure 9: Effect of gap transpiration on the blade pressure distribution at 0.95R radius for an intermediate J](image2)

**4.3 Duct trailing edge**

Potential flow methods are not very suitable for modeling the flow around lifting surfaces that have a blunt trailing edge. In practical applications most ducts however have blunt trailing edges. When BEM like PROCAL are used to analyze such geometries they will predict unrealistic low pressure peaks at the locally strongly curved trailing edge. Moreover, a duct geometry like that will certainly hamper the blade wake alignment process. Therefore the trailing edge of the duct must be made sharp in some way. One can think of many ways to do this. From a physical point of view it is probably most realistic to extend the duct in downstream direction while attempting to model the separated region downstream of the duct trailing edge.

In the sensitivity study for the MARIN CRS PROCAL working group Wärtsilä carried out extensive variations of the sharp duct trailing edge. The radial location of the duct trailing edge appeared to be most relevant. Figure 10 shows cross sections of the duct variants that were used alongside the actual 19A duct geometry. The red variant with the trailing edge on the inner duct surface extension is almost identical to the 19Am duct that was used by Baltazar et al. (2012). They showed by means of model tests that this duct only leads to slightly different open water characteristics than the 19A duct.

![Figure 10: Variation of the radial position of the duct trailing edge. Black: actual 19A duct geometry, red: duct TE on inner surface extension, green: duct TE in the middle, blue: duct TE on the outer surface extension.](image3)

Figure 11 shows the effect of the radial duct trailing edge position on the open water characteristics. There is a strong impact on the propeller thrust and torque, but the effect on the duct thrust is only limited. A larger radial TE position results in a larger diffuser angle of the duct. The outlet pressure must be identical for all ducts as it is governed by the ambient pressure. According to classical momentum theory - see for instance Zondervan et al. (2006) - the outlet velocity is related to the propeller thrust. Therefore a larger diffuser angle results in a higher flow rate through the duct and consequently in a reduction of propeller thrust and torque.

![Figure 11: Effect of the radial duct trailing edge position on the open water characteristics](image4)
The fact that the flow rate increases while the duct thrust is almost identical may seem contradictory at first. The larger flow through the duct is associated with a larger circulation around the duct. For this larger circulation one would also expect a larger duct force.

Figure 12 shows the radial force that acts on the duct. Please note that the radial duct force is mainly negative. It is zero at the top of the chart area. Now things get more clear. The larger circulation for the duct geometries with a larger radial TE position result in an increase (in absolute sense) of the radial duct force rather than in an increase of the duct thrust.

Figure 13 shows the pressure distribution on the duct for an intermediate advance ratio. The duct LE is at x/R = 0.5 and the duct TE is at x/R = -0.5. C\textsubscript{pn} is zero at the horizontal black line. The figure clearly shows that the radial duct TE position mainly affects the pressure downstream of the propeller. In this area the normal vector only has a small component in axial direction. Therefore there is little effect on the duct thrust and a large effect on the duct radial force.

Figure 14 shows a comparison of the open water predictions of MPUF-3A/Fluent with the Star-CCM+ RANS results and experiments for the Ka4-70 propeller in 19A duct. The chart shows MPUF-3A results for two different interaction options with Fluent. This interaction process with Fluent is described in Section 2.1. The interaction option only has a small effect on the computed open water characteristics.
The MPUF-3A/Fluent and the Star-CCM+ results are in very reasonable agreement with the experiments. MPUF-3A somewhat over predicts the propeller thrust and torque, while Star-CCM+ somewhat under predicts. The agreement for duct thrust and efficiency is good.

Figure 15 shows a comparison of open water predictions of PROCAL with Star-CCM+ and experiments for the Ka 4-70 propeller in 19A duct. Around J=0.5 the PROCAL results are in very good agreement with the experiments. However, at low and at high advance ratios PROCAL over predicts the experiments. Star-CCM+ seems to do a better job in this respect; there is some offset with respect to the experiments, but it is more consistent. PROCAL over predicts the duct thrust for all advance ratios, in particular for high Js where the flow separates on the duct outer surface. This also results in an over prediction of the efficiency. In these PROCAL calculations the duct trailing edge was located on the extension of the inner duct surface. It is easy to make the PROCAL propeller thrust match the experiments or RANS results by changing the radial location of the (sharp) duct trailing edge (see Section 4.3).

Again the PROCAL results are in good agreement with the experiments for intermediate advance ratios, but the duct thrust and the efficiency are over predicted, in particular for high advance.

![Figure 15: Open water characteristics for the Ka 4-70 propeller in 19A duct; Comparison of PROCAL with Star-CCM+ and Experiments](image)

**5.2 Span-wise blade loading**

Figure 17 shows a comparison of the span-wise blade loading calculated by MPUF-3A and Star-CCM+. In this figure the sectional lift coefficient is plotted as function of the radius. It is common practice to compare the span-wise loading of propellers in terms of circulation distribution, but this quantity is difficult to extract from RANS results. Therefore it was decided to compare the sectional lift coefficient which is defined as

\[
C_L = \int_{x=0}^{1} \Delta C_{pn} \cdot dx
\]

where \(\Delta C_{pn}\) is the jump of the pressure coefficient from suction to pressure side and \(x\) is the non dimensional chord station. Multiplication of \(C_L\) with \(\frac{1}{2} \rho n^2 D^2 C\) will yield the sectional lift per unit span, where \(\rho\) is the water density, \(n\) is the propeller rate of revolution, \(D\) is the propeller diameter and \(C\) is the chord length. This sectional lift does of course not include any contribution of shear force, and the direction is perpendicular to the pitch of the subject section.

Figure 17 shows MPUF-3A results for different interaction options with Fluent (see Section 2.1). The effect of the interaction option on the load distribution is considerable. This is remarkable as the effect on open water characteristics was only small. On average MPUF-3A/Fluent predict a higher lift than Star-CCM+. This is consistent with the higher propeller thrust and torque of MPUF-3A in Figure 14.
Interaction option 5 results in a slower inflow in the tip area than interaction option 3. This results in a higher loading at the tip. Moreover the deceleration of the flow also results in a curved flow that virtually increases the camber. This also increases the load at the tip. At low and intermediate radii Option 5 results in a faster inflow (averaged over the chord) which results in a lower propeller loading than Option 3. Please note that at the leading edge the difference in wake is only small. The evaluation plane for Option 3 is close to the leading edge. The total lift for Option 3 and Option 5 is about equal. Therefore there is hardly an effect on the open water curves.

Figure 19 shows a comparison of the span-wise load distribution as calculated by PROCAL and Star-CCM+. PROCAL also outputs the sectional axial and tangential force. From these data the sectional contribution to $K_T$ and $K_Q$ can be calculated. In Star-CCM+ comparable data were calculated by integrating the pressure over narrow span-wise strips. PROCAL is in much better agreement with the RANS results than MPUF-3A.

5.3 Pressure distributions

Figure 20 and Figure 21 show comparisons of pressure distributions on the blade of the Ka 4-70 propeller in 19A duct at $J=0.5$ for different radii. They show predictions by MPUF-3A and Star-CCM+. Again results for interaction options 3 and 5 are shown. The MPUF-3A results are in reasonable agreement with the Star-CCM+ RANS results. It is not directly clear if one of the interaction options yield results that correlate better with RANS than the other.
Figure 20: Pressure distribution on the blades of the Ka4-70 propeller in 19A duct at J=0.5 at 0.7R radius; Comparison of MPUF-3A and Star-CCM+

Figure 21: Pressure distribution on the blades of the Ka4-70 propeller in 19A duct at J=0.5 at 0.9R radius; Comparison of MPUF-3A and Star-CCM+

Figure 22: Pressure distribution on the blades of the Ka4-70 propeller in 19A duct at J=0.5 at 0.7R radius; Comparison of PROCAL and Star-CCM+

Figure 23: Pressure distribution on the blades of the Ka4-70 propeller in 19A duct at J=0.5 at 0.9R radius; Comparison of PROCAL and Star-CCM+

Figure 24: Pressure distribution on the 19A duct around the Ka 4-70 propeller at J=0.5 and θ=0 deg; Comparison of PROCAL and Star-CCM+

Figure 22 and Figure 23 also show comparisons of pressure distributions on the blade of the Ka 4-70 propeller in 19A duct at J=0.5. These figures show predictions by PROCAL and Star-CCM+. The PROCAL results are generally in very good agreement with the RNS results. Only very close to the tip the results start to deviate.

Figure 24 shows a comparison of the pressure distribution on the 19A duct around the Ka 4-70 propeller at J=0.5. It shows predictions by PROCAL and Star-CCM+. It applies to a longitudinal section at θ=0 deg which is at the blade reference line. The sudden pressure jump at the blade tip (x=0) is clearly visible. Star-CCM+ predicts a low pressure peak just upstream of the blade tip. This peak is not predicted by PROCAL. Further upstream PROCAL is in fairly good agreement with RANS. It predicts slightly lower pressures.
Figure 25 and Figure 26 also show comparisons of the pressure distribution on the 19A duct around the Ka 4-70 propeller at J=0.5. These figures apply to transverse sections at x = 0.25 (upstream of the propeller) and x = -0.2 (downstream of the propeller). Next to the PROCAL and Star-CCM+ results these figures also show experimental results (green lines). They plot the pressure (-C\text{pn}) as function of the angular position \( \theta \). The lines that strongly vary with \( \theta \) apply to the inside duct surface. The lines that are almost constant apply to the outer duct surface.

Upstream of the propeller (Figure 25) all results are in excellent agreement, but downstream of the propeller (Figure 26) the agreement is not good. There the results only agree in terms of the average value.

Figure 25: Pressure distribution on the 19A duct around the Ka 4-70 propeller at J=0.5 and x/R=0.25; Comparison of PROCAL with Star-CCM+ and experiments

Figure 26: Pressure distribution on the 19A duct around the Ka 4-70 propeller at J=0.5 and x/R=-0.2; Comparison of PROCAL and Star-CCM+ and experiments

Figure 27: Pressure contours on the inside of the 19A duct around the Ka4-70 propeller as computed by Star-CCM+

The presence of this gap vortex explains the low pressure peak upstream of blade tip in Figure 24. This vortex is not modeled in PROCAL and therefore PROCAL cannot predict the pressure peak. The pressure variations in Figure 26 are also mainly due to this vortex. Therefore PROCAL predicts almost no pressure variation. Vortices always tend to dissipate quickly in RANS calculations. This explains why the amplitude predicted by Star-CCM+ is smaller than the amplitude of the experiments. One can also imagine that it is difficult to predict the pitch of the gap vortex completely correct. This explains the phase difference between Star-CCM+ and the experiments. Finally, the numerical dissipation of this vortex also may explain why Star-CCM+ under predicts the propeller thrust and torque for the Ka4-70 propeller (see Figure 14).
6 UNSTEADY CAVITATING RESULTS
This section presents unsteady cavitating results of MPUF-3A for the TSHD Uilenspiegel. The unsteady capabilities of PROCAL are still under development.

The results in this section do not follow from interaction of MPUF-3A with RANS. Instead a radially distributed duct induction velocity field was assumed. The magnitude of the duct induced velocity was varied in order to arrive at the same propeller thrust as in the model experiments. In the MPUF-3A calculations the image singularities that represent the duct inner surface were switched on.

Figure 28 shows a comparison of the cavitation pattern that was calculated by MPUF-3A with model tests observations at MARIN. The MPUF-3A results show the cavity thickness at a number of radii, where the thickness is plotted in radial direction with respect to a base line. Despite the somewhat simplified approach the MPUF-3A results are in very reasonable agreement with the observations. It only seems that MPUF-3A over predicts the cavity thickness at the tip. It is however very difficult to estimate the cavity thickness from the model test pictures.

From other cavitation tests with ducted propellers it is known that there often is a relatively thin cavity on the duct surface between the blade tip and a leading edge or gap.
vortex that has a pitch that is reduced significantly with respect to the propeller pitch (Figure 27). Figure 29 shows an example of such a cavity. The relatively thick cavity that MPUF-3A predicts at the tip is in some way representative for this cavity.

Figure 29: Example of the cavity at the tip of a ducted propeller.

7 CONCLUSION
This paper showed various computational results for ducted propellers. The results were compared with each other and with experiments.

The RANS results are in good agreement with experiments, both in terms of open water characteristics and pressure distribution on the duct. Only downstream of the propeller on the inside of the duct there were significant differences that can be attributed to a mismatch of the strength and pitch of the gap vortex.

The potential codes MPUF-3A and PROCAL are both in reasonable agreement with the experimental and RANS results. Particularly the pressures on the blade and duct of PROCAL agree very well with the RANS and experimental pressures.

Cavitation predictions of MPUF-3A agree well with model test observations.

Based on the results it can be concluded that Potential flow codes are a useful supplement to RANS simulations for the efficient design of ducted propellers.

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DISCUSSION
Question from Sverre Steen
As a propeller designer, how do you deal with the problem of selecting the “right” position of the trailing edge point of
the duct when there are no model test results to compare with?

**Authors’ closure**

It appears that the optimum trailing edge position does not strongly depend on the propeller geometry. Within the MARIN CRS PRODUCT working group a validation study was done for several D-series propellers (varying blade area ratio, design pitch and pitch setting) in 19A duct. All computations were done with the same duct TE point. The deviations from the experiments appeared to be very systematic: an overestimation of propeller thrust and torque at low and high advance ratio, a more or less correct prediction of propeller thrust and torque at intermediate J and a general over-prediction of duct thrust, particularly at high J. The optimum duct TE position depends more on the duct type and on the relative advance ratio than on the propeller. Therefore PROCAL can be used efficiently during the propeller design after some experience has been gained with the duct that is used.

**Question from Tobias Huuva**

Do you think that there is possibility to also use potential flow methods for low J values?

**Authors’ closure**

Yes, I think that this is very well possible. The flow around a ducted propeller at low J is less prone to flow separation than that around an open propeller. Problem is however that the wake alignment process, which is very important to get good results, is not as robust as one would like, particularly at low advance ratios. Therefore the MARIN CRS PRODUCT2 working group is now working to improve the robustness and efficiency of the code by applying only a limited number of span-wise and stream-wise stations where the wake pitch is aligned with the flow together with interpolating regression functions. In addition to that an appropriate location of the duct TE position must be established for very low advance ratios.