Validation studies of a boundary element method for ducted propellers

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ABSTRACT
This paper provides an overview of several validation studies that were carried out for a Boundary Element Method (BEM) for ducted propellers. These studies comprise validation of open water characteristics, pressure distributions, blade forces at inclined inflow and steady and unsteady cavity extent. The results of the BEM are compared with model test data, RANS results and full scale cavitation observations.

Keywords
Ducted propellers, Boundary Element Method (BEM), Validation.

1 INTRODUCTION
For high thrust loadings, ducted propellers offer a significantly higher efficiency than open propellers. Therefore almost all vessels that have a high thrust loading, such as tugs, fishing vessels and dredgers are equipped with ducted propellers. Ducted propellers are also widely used in the offshore industry for dynamic positioning. Before the crisis in the offshore industry more than half of the propellers that were manufactured by Wärtsiål and Caterpillar were ducted. Also after the collapse of the offshore market the portion of ducted propellers remains substantial.

The design of ducted propellers requires an accurate and efficient tool for the hydrodynamic analysis of these propellers. RANS methods can give very accurate results for ducted propellers. However, the time that is required for preprocessing, computations and post processing is often too long for a design process in which several iterations are carried out, where each iteration involves hydrodynamic calculations for a number of operating conditions. Therefore, Boundary Element Methods (BEM) are still a good alternative. They give reasonably accurate results, while the computational time is much shorter.

During the past 15 years the MARIN CRS (Cooperative Research Ships) has developed and validated the Boundary Element Method PROCAL that can predict steady and unsteady forces and cavitation for marine propellers. Recently PROCAL was extended to make it suitable for ducted propellers.

This paper presents an overview of the validation studies of PROCAL for ducted propellers. Section 2 presents a concise description of the method. It addresses the extensions that were necessary to enable application of PROCAL to ducted propellers. Subsequently, this paper presents results of the validation studies that were performed. These studies include:

Wetted forces in open water. Detailed studies were done for the Ka 4-70 and D 4-70 propellers with a pitch ratio of 1.0, operating in 19A and 37 ducts. Furthermore, less detailed studies were done for a wider selection of propellers, including the Ka and D Series, that operate in various ducts. These studies are presented in Section 3.

Wetted forces at inclined inflow. The PROCAL results for a newly designed five bladed propeller operating in a 19A duct at inclined inflow are compared with model experiments and RANS calculations. This study is presented in Section 4.

Cavity extents in open water. The cavity extents that PROCAL predicts for the Ka4-70 and D4-70 propellers (P/D = 1.0) operating in a 19A duct are compared with model experiments. This is presented in Section 5.

Unsteady cavity extents. The cavity extents for non-
uniform inflow on the ducted propeller of a VLCC were calculated by PROCAL using a nominal wake field. See Section 6.

2 DESCRIPTION OF THE METHOD

The BEM PROCAL has been developed for the unsteady analysis of cavitating propellers operating in a prescribed ship wake. It has been validated for open water characteristics, shaft forces and moments, sheet cavitation extents and propeller induced hull-pressure fluctuations. The code is a low order BEM that solves for the velocity disturbance potential using the Morino formulation. The applied model for sheet cavitation is based on the formulation by Fine and Kinnas (1993). Validation studies and details on the mathematical and numerical model can be found in Vaz & Bosschers (2006). The geometry of the blade wake can be determined by an iterative procedure to align the propeller wake with the flow or by prescribing the wake pitch and contraction using empirical formulations to reduce CPU time.

PROCAL has been coupled to the acoustic boundary element method EXCALIBUR (Van Wijngaarden 2011), to compute the hull pressure fluctuations at the blade rate frequency (Bosschers et al. 2008, Lafeber et al. 2009). An empirical model is used to predict the broadband hull pressure fluctuations and underwater radiated noise by the cavitating tip vortex (Bosschers 2018). The method is used in an automated propeller design procedure (Huisman & Foeth 2017).

PROCAL has been coupled with RANS to predict the powering performance of ships and to predict the effective wake field (Starke & Bosschers, 2012, Rijpkema et al. 2013, Hally 2018).

For the analysis of ducted propellers a similar method as proposed by Baltazar et al. (2012) has been implemented. An iterative wake alignment method is used for the wake of the propeller and duct in which the radial position of the trailing vortices is prescribed while the pitch is obtained from the computed induced velocities. The velocities near the duct surface are reduced in value depending on a user specified boundary layer thickness. The gap between propeller blade and duct is modeled as a surface on which the transpiration velocity can be prescribed, but, usually, the gap is modeled as a rigid surface. The duct trailing edge geometry is modified such that a sharp trailing edge is present and the location from which the vortices trail from the duct is clearly defined. An iterative pressure Kutta condition is applied in which the wake strengths of duct and propeller are modified until the pressure difference on the two surfaces at the trailing edge of blade and duct is smaller than a user specified value. A RANS-BEM coupling procedure has been developed to analyze the influence of the blunt trailing edge of the duct, see Bosschers et al. (2015). Validation studies of PROCAL for ducted propellers operating in open water conditions have also been presented by Moulijn (2015).

For the unsteady analysis of the ducted propeller performance, a similar procedure as used for open propellers is used: The solution at each time step is computed for a key blade, a key hub, and a key duct surface to minimize the number of unknowns in the system of equations to be solved. The solution for the other surfaces is taken from previous time steps. The key duct surface is 1/Z part of the total duct surface that is wrapped around the key blade, where Z is the number of propeller blades. This is illustrated in Figure 1.

Figure 1: Distribution of key surfaces (blue shading) and symmetry surfaces (green shadings) for a ducted propeller in unsteady flow.

3 VALIDATION IN OPEN WATER

This section presents the results of validation studies for fully wetted open water conditions

3.1 Detailed studies

First the results of detailed validation studies performed by Caterpillar and Wärtsilä are presented. PROCAL results for the Ka 4-70 and D 4-70 propellers are compared with the results of model experiments and RANS calculations. Both propellers have a pitch to diameter ratio of 1.0, and are operating inside the well known 19A and 37 accelerating ducts. More information on the Ka propeller series and the duct geometries can be found in the Wageningen B-Series book by Kuiper (1992). Dang et al. (2013) provide more information on the D-Series propellers.

For this validation study, dedicated model experiments were done in the deep-water towing tank of MARIN. The propeller thrust and torque and the duct thrust were measured in a regular open water test set-up. The 19A duct was equipped with a number of pressure transducers at various chord-wise and angular positions.

The RANS calculations were done by Wärtsilä using StarCCM+, version 11.04. The turbulent flow is numerically solved on a computational domain.
surrounding the propeller-duct-shaft system. A cylinder aligned with the shaft of the propeller is selected as computational fluid domain (see Figure 2).

Figure 2: Computational domain for the RANS calculations

The flow field is calculated by means of quasi-steady segregated flow solver techniques, using numerical schemes based on SIMPLE algorithms, together with hybrid Gauss-LSQ gradient approximations. Turbulence is modeled by means of the standard SST k-ω two-equation model. The propeller motion is incorporated via a moving frame of reference (MFR).

A uniform velocity distribution is prescribed for the inlet boundary condition. Pressure conditions are applied on the outlet and circumferential boundaries of the cylindrical outer domain. Wall-bounded boundaries obey a no-slip condition.

Unstructured hexahedral cells are used to build the computational mesh. The computational domain consists of two distinct regions: a non-rotating main cylinder (12Dprop x 5Dprop), and a rotating MFR domain (2Dprop x 0.75Dprop), which contains a small section of the shaft and the ducted-propeller configuration. Various grid refinements are applied to ensure proper flow convergence. The prism layer distribution near solid walls are adapted to obtain y⁺ values below 1. A smooth transition between near-wall and background mesh is obtained using a geometric stretching formulation. Typically 10-15 layers are required. This result in a mesh of about 6M cells.

The validation studies commenced with extensive sensitivity studies. The PROCAL results appear to be particularly sensitive to the trailing edge geometry of the duct. The in-viscid BEM requires that lifting surfaces like propeller blades and ducts have a sharp trailing edge. Practical ducts, however, always have a thick blunt trailing edge. Therefore, the duct trailing edge must be modified. Figure 3 shows an example of different ways to equip the 19A duct with a sharp trailing edge. It appears that the radial location of the modified sharp trailing edge has a particular strong influence on the calculated propeller thrust and torque. An increase of the radial duct trailing edge location results in larger duct loading which causes a decrease of the propeller thrust and torque. It is remarkable that the duct thrust is hardly affected by the trailing edge location. The increase of the duct loading is mainly reflected by an increased radial force on the duct. Moulijn (2015) provides more elaborate results and discussions on the effect of the duct trailing edge on the results of PROCAL. Bosschers et al. (2015) have presented a method where PROCAL is coupled to a RANS solver. This method can remedy the dependence of the PROCAL results to the duct trailing edge location.

Figure 3: Different ways to create a sharp duct trailing edge on a 19A duct.

Another aspect that proved to be very important for the results of PROCAL is the alignment of the wake of the blades. The effect of wake alignment is much stronger for ducted propellers than for open propellers. The wake pitch has a strong effect on the loading of the duct, and therewith also on the propeller thrust and torque. However, for very low advance ratios the convergence of the iterative wake alignment process is often cumbersome.

The effect of the computational grid in PROCAL was also studied extensively. Figure 1 provides an illustration of a typical grid. For the blade a grid of 30 span-wise by 30 chord-wise (for only one side) panels gives practically converged results. For the duct 20 panels are used in circumferential direction between successive blades (i.e. one segment), while in chord-wise direction 90 panels are used on the inside and 30 panels are used on the outside.

Figure 4 and Figure 5 present comparisons of the open water characteristics of the Ka 4-70 and D 4-70 propellers. The non-dimensional thrust and torque coefficients are defined as follows:

\[ K_{TP} = \frac{T_P}{\rho n^2 D^2}, \quad K_{TD} = \frac{T_D}{\rho n^2 D^2}, \quad K_Q = \frac{Q}{\rho n^2 D^2}, \]

where \( T_P \) is the propeller thrust, \( T_D \) is the duct thrust, \( Q \) is the (propeller) torque, \( \rho \) is the water density, \( n \) is the rate of revolutions of the propeller and \( D \) is the propeller diameter. Furthermore, the efficiency of the propeller is represented by the curves designated \( \eta \). They are plotted as function of the advance coefficient \( J = V_a/(nD) \). Each figure shows PROCAL results, RANS results and experimental results. In Figure 5 the axes have been blanked because of confidentiality of the D-Series.
The RANS calculations and the experiments are in very good agreement, but the PROCAL results show somewhat larger deviations. In these calculations the duct trailing edge location was tuned to make the propeller thrust match the experimental results at the design point ($J \approx 0.5$). At low and high advance ratios the propeller thrust and torque are overestimated. The duct thrust is always overestimated. This also causes an overestimation of the efficiency.

The open water characteristics for the Ka 4-70 and D4-70 propellers in the 37 duct are not included in order to prevent a too long paper. It is however remarked that they compare in a similar manner as the 19A results, even though the 37 duct is more challenging because of its much thicker trailing edge.

Figure 6, Figure 7 and Figure 8 show comparisons of pressure distributions on the Ka 4-70 propeller in the 19A duct. They plot the non-dimensional pressure coefficient $C_{pn} = (p - p_{shag})/(0.5 \rho n^2 D^2)$ as function of the location on the blade or duct. Figure 6 shows the pressure on the blade at 0.7R radius. Figure 7 plots the pressure on the duct at a fixed angular position ($\theta = 0^\circ$) on the duct as function of the axial location. The angular location corresponds to the middle of the blade tip of the propeller. Figure 8 plots the pressure on the duct at a fixed axial location ($x/R = 0.25$) as function of the angular position. Figure 6 and Figure 7 compare PROCAL and RANS results. Figure 8 compares PROCAL, RANS and experimental results.

The pressures are generally in excellent agreement. The blade pressures only differ slightly at the trailing edge where viscous effects get more important. Figure 7 shows that there is a significant difference in the duct pressure just upstream of the propeller blade (which is located at the large pressure jump at $x/R = 0$). The pressure peak in the RANS results is absent in the PROCAL results. This peak is caused by the tip leakage vortex which is missing in the PROCAL calculation. Figure 8 shows that upstream of the propeller the pressures are in good agreement. This figure clearly shows the pressure field that is induced by the four propeller blades on the inner surface of the duct. PROCAL predicts slightly lower pressures. Together with the over-prediction of the pressure and the geometric modifications at the duct trailing edge this is an explanation for the over-prediction of the duct thrust. It must be remarked that the duct pressures downstream of the propeller do not agree that well. This is due to the tip leakage vortex which is absent in the PROCAL calculations. In the RANS calculations this vortex dissipates too quickly and the pitch is also slightly off.
3.2 Validations for a wider selection of propellers and ducts

Next to the detailed validation studies that were presented in the previous paragraph, the PROCAL open water characteristics were also validated against a wider selection of propellers and ducts.

Damen did a validation study where the PROCAL predictions of open water characteristics are compared with the experiments from the C-D-Series JIP (Dang et al 2013). Table 1 presents an overview of all geometries that were addressed. The study comprises a variation in blade area ratio, a variation in design pitch ratio and two variations in pitch setting (for two different propellers). The D-Series is a series of 4-bladed ducted controllable pitch propellers, so blade number was not varied. In the design pitch variation the blades are set according to their design pitch (i.e. not rotated). In the pitch setting variations the blades of the same propeller were adjusted (i.e. rotated) to a different pitch. The latter also causes a strong variation of the pitch distribution. For a pitch setting of $P_{0.7}/D = 0.5$, the low pitch at the tip resulted in a too strongly distorted panel mesh on the duct with the present panel generator. Therefore no PROCAL results were obtained. In this study all propellers were operating in a 19A duct.

Figure 9 presents a typical result of this study. It shows the difference with respect to experiments of the propeller and duct thrust and the propeller torque for the D4-40, $P_{\text{design}}/D = 1.4$ propeller at $P_{\text{set}}/D = 1.6$, operating in a 19A duct. The differences are made non-dimensional by means of the experimental values at $J = 0.0$. The duct thrust is always overestimated. In this case the duct trailing edge was located slightly more outward than in the detailed validation case. This results in a small underestimation of the propeller thrust and torque except for the low and high J-range. All propellers in this study show very similar deviations. In the low J-range the results show a difference in trend because the convergence of the wake alignment process is more cumbersome.

<table>
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<td>0.40</td>
<td>1.4</td>
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</tr>
</tbody>
</table>

Figure 9: Difference between computations and experiments in $K_T$, $K_Q$ and $K_O$ for the D4-40, $P_{\text{design}}/D = 1.4$ propeller at $P_{\text{set}}/D = 1.6$

CETENA did a similar validation study for the Ka propeller series. The Ka propellers are a series of fixed pitch ducted propellers. They are distinctly different from the D-Series propellers in that they have a large chord length at the blade tip. This study also included different blade numbers as well as different ducts: 19A, 22 and 24. The outline of the 22 and 24 ducts is identical to that of the 19A duct, but their chord is much longer. More information on the Ka propeller series and the duct geometries can be found in the Wageningen B-Series book by Kuiper (1992). Table 2 provides an overview of the propeller-duct combinations that were investigated. In all cases the propeller had a pitch ratio (P/D) of 1.0.
This validation study confirmed the results of the previous open water validations. The propeller thrust and torque are about correct (may be slightly under predicted) at the design point \( (J = 0.5) \) and somewhat over predicted at low and high Js. The duct thrust is always over predicted, in particular for high J (see Figure 4, Figure 5 and Figure 9). For the longer 22 and 24 ducts the over prediction at high J is even stronger. Figure 10 shows a comparison of experimental and PROCAL open water characteristics for the Ka 4-70 P/D = 1.0 propeller that operates in a 24 duct. RANS calculations indicate that the flow separates on the outside of the duct for high J-values. This is obviously not captured by PROCAL resulting in the over prediction of the duct thrust. Apparently this effect is stronger for the longer ducts.

4 VALIDATION AT INCLINED INFLOW

Dedicated model experiments were done to validate PROCAL for a ducted propeller under inclined inflow conditions. For these tests a new 5 bladed propeller was designed with some tip unloading, skew, and a small chord length at the tip. The duct was again the well known 19A duct.

The experiments were carried out in the deep water tank of MARIN. The shaft was vertically inclined at 0°, 5°, 10° and 15°. At 0° inclination the regular open water characteristics were measured for the full J-range from \( J = 0 \) up to \( K_T = 0 \). The 5°, 10° and 15° inclined inflow tests were done for 2 advance ratios: \( J = 0.3 \) and \( J = 0.5 \). One of the five blades was mounted to a six-component force transducer that was located inside the hub of the model propeller. This resulted in a unique dataset for the blade forces on a ducted propeller under inclined inflow conditions. The duct force was measured in axial direction only.

CETENA made RANS and PROCAL calculation for this propeller-duct combination. The PROCAL calculations were done for both \( J = 0.3 \) and \( J = 0.5 \), but the RANS calculations were only done for \( J = 0.5 \).

The RANS calculations were made by means of the commercial finite volume based solver STAR CCM+ applied to an unstructured polyhedral mesh consisting of around 8.5 M cells for the rotating part and 10 M cells for the outer fixed fluid domain (Figure 12). The mentioned grid blocks are connected following a sliding mesh formulation. The fluid domain for the inclined flow condition can be easily obtained by rotating the propeller, duct hub and inner cylinder to achieve the desired angle,
as is shown in Figure 13. Figure 14 shows a close-up of the computational grid in the gap between the blade and the duct. The standard k-ε model was used with a two layer approach using wall functions. The time step selected for the unsteady computation corresponds to a blade angular displacement of 1 degree.

Figure 12: Resulting volume mesh

Figure 13: Fluid domain for inclined inflow

Figure 14: Detail of the grid in the blade-duct gap

Figure 15 shows a comparison of the computational and experimental values for the mean axial forces and moment for J = 0.5 and an inclination angle of 10°. The PROCAL propeller thrust matches the experiments very well. In the PROCAL calculations the radial position of the trailing edge of the duct was tuned to make the propeller thrust match the experiments at 0° inclination. The effect of the inclination on the axial forces is only small. Like with the open water cases in Section 3 PROCAL over predicts the duct thrust.

The RANS calculations somewhat over predict the propeller thrust and torque. It however must be remarked that the experimental values follow from measurements on a single blade which is prone to be less accurate than thrust and torque measurements of a complete propeller. For the duct thrust the RANS and experimental results are in good agreement.

Figure 16 and Figure 17 show comparisons of the computed and measured (single) blade forces and moments. They are given with respect to a right handed Cartesian coordinate system that rotates with the propeller. The x-axis coincides with the centerline of the propeller rotational axis and points in forward direction. The z-axis coincides with the directrix of the blade. The y-axis completes the coordinate system. The propeller is also right-handed. The centrifugal forces were subtracted from the measured forces. All forces and moments are plotted as function of the blade angular position, where 0° is the top position.

The computational and experimental results are in good agreement. The over prediction of propeller thrust and torque by RANS is again clearly present. Both PROCAL and RANS predict more or less the correct amplitude, but there seems to be a slight shift of the phase with respect to the experiments. For the other inclination angles and advance ratio the correlation between computations and experiments is similar.

Figure 15: Comparison of KTP, KTD and 10KQ for J = 0.5 and an inclination of 10°

Figure 16: Comparison of single blade forces for J = 0.5 and an inclination angle of 10°
5 VALIDATION OF STEADY CAVITY EXTENTS

Another set of dedicated model tests was done to validate the steady cavitation predictions of PROCAL. The Ka 4-70 and D 4-70 propellers, both with a P/D = 1.0 and both operating in a 19A duct, were tested in MARIN’s Depressurized Wave Basin (DWB). The tests were done for two advance ratios, J = 0.2 and 0.5, and five cavitation numbers, $\sigma_n = 1.1^1, 1.3, 1.5, 1.7$ and 1.9. All tests were conducted at a propeller rate of revolutions of 1100 RPM. During these tests roughness was applied to the leading edges of the blades to trip turbulent flow, and nuclei were generated by means of a fine electrolysis grid that was located upstream of the propeller. In this case a transparent duct was used which enables adequate lighting of the propeller and also allows for observation of cavitation in the gap between propeller and duct through the duct. The propellers were observed by means of a high speed camera.

The observations are compared with steady cavitation predictions of PROCAL. Although the inflow to the propeller and duct is practically uniform, there is still some variation of the hydrostatic pressure over the propeller disk, which results in a slightly in-stationary cavity in the experiment.

Figure 18 clearly shows variations with a period of 360° and variations with a period of 72°. The first variation is due to inclined inflow, while the latter is due to the five propeller blades. The PROCAL and RANS results are in good agreement.

MTG did the PROCAL simulations for the Ka 4-70 propeller. Figure 19 and Figure 20 show comparisons of the experimental and calculated cavity patterns. Figure 19 applies to J = 0.2 and $\sigma_n = 1.3$, and Figure 20 compares results for J = 0.2 and $\sigma_n = 1.9$. In the PROCAL results the cavity, that is represented by the blue-grayish surface, is only shown on the key blade which is in the top position. The colored contours on the blade represent the pressure distribution. The color map range is from $C_{pn} = 0$ at blue to $C_{pn} = -\sigma_n$ at red. The distinct red triangles on the symmetry blades in Figure 20 correspond to the area that is covered with sheet cavitation. Here the pressure equals vapor pressure, so $C_{pn} = -\sigma_n$. This also applies to Figure 19. Both figures show a good agreement of the cavity pattern on the blade. PROCAL underestimates the thickness of the cavity at the blade tip. This, however, is probably due to the absence of a tip leakage vortex in the calculations. Figure 19 shows bubble cavitation for the experimental cavity pattern. In PROCAL this is represented by a sheet cavity that detaches in the mid-chord region.

Wärtsilä made the PROCAL calculations for the D 4-70 propeller. Figure 21, Figure 22 and Figure 23 subsequently show comparisons of the experimental and calculated cavity patterns for J = 0.2 at $\sigma_n = 1.1$, J = 0.2 at $\sigma_n = 1.5$ and J = 0.5 at $\sigma_n = 1.5$. For this propeller no observations were made through the transparent duct. The calculated cavity is represented by the very light blue surface. It is again shown on the key blade only, which is for this case shown on the left. Also here the red color means to pressure equal to (or lower than) vapor pressure. These figures also show a very good agreement of the calculations with the experiments. Again the tip leakage vortex is absent in the PROCAL results.

1 D 4-70 propeller only
6 VALIDATION OF UNSTEADY CAVITY EXTENTS
Caterpillar performed a validation study for the unsteady cavity predictions of PROCAL. The test case was a 280 000 dwt VLCC M.S. Thorsaga that is equipped with a 7.3m ducted propeller (Narita et al, 1974).

A RANS based CFD method using OpenFOAM and k-ω SST was used to simulate the nominal wake field for the bare hull and to simulate the ducted propeller operating behind the hull.

The nominal wake field from CFD was used as inflow to the propeller and duct in PROCAL. The nominal wake field can be seen in Figure 24. Using the nominal wake field with PROCAL implies that the interaction of the propeller and duct induced velocity with the wake field is ignored.

The PROCAL simulation was setup to match the power in the CFD simulation by adapting the ship speed. The results show an overestimation of the duct thrust and an underestimation of the propeller thrust.

Comparison of the PROCAL simulation in the nominal wake field with the CFD simulation of the ducted propeller behind the hull shows that PROCAL overestimates the thrust variation, see Figure 25.

A wake sensitivity study was performed which showed that the propeller and duct thrust variation is mostly affected by the axial wake. It was also seen that the radial wake had a large effect on the radial force on the duct. This was deemed not realistic. A more reasonable duct loading was found by setting the radial velocity for the duct explicitly to zero. This improved the propeller thrust and torque because of the more realistic duct induced velocity.
PROCAL was also used to simulate the propeller operating in an effective wake field, calculated iteratively by subtracting the PROCAL induced velocities from the total wake computed by the full CFD. The results show improved prediction of thrust variation and cavitation, while the velocity induction from the duct remain exaggerated. An alternative methodology to predict the effective wake field using RANS-BEM coupling for ducted propellers is still under development. This procedure is similar to the method of Rijpkema et al. (2013).

7 CONCLUSIONS
This paper gave an overview of the achievements of the MARIN CRS PRODUCT and PRODUCT2 working groups, that extended the Boundary Element Method PROCAL to enable application to ducted propellers. The method was extensively validated by several members of the CRS. From these validation studies the following conclusions were drawn.

- PROCAL provides reasonably accurate predictions of the open water characteristics of ducted propellers. The deviations appear to be systematic and relatively independent from the propeller and duct geometries.
- The results strongly depend on how the duct trailing edge is modified into a sharp geometry that is suitable for potential flow methods. However, once a good trailing edge geometry has been established for a certain duct type, it will be adequate for other propellers that operate inside that duct.
- The pressure distributions that PROCAL predicts are in good agreement with RANS predictions and experiments.
- PROCAL accurately predicts the unsteady blade forces on a ducted propeller that operates at an inclined inflow.
- Although the cavitation model of PROCAL lacks some robustness, the results are very promising. They give a very realistic impression of the cavitation pattern.

All in all PROCAL appears to be a useful design tool that provides good results at relatively low cost (i.e. time required for preparation, computation and post-processing).

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