Effect of Propeller Tip Clearance on Hull Pressure Pulses

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ABSTRACT
The objective of this study was to investigate how hull forces and pressure are influenced by small propeller tip clearance by creating a set-up where systematic variation of tip clearance could be achieved at similar propeller conditions; in this study, clearances between the propeller tip and a generic hull with tunnel configuration were 0.7\(\%D_P\), 5\(\%D_P\), and 20\(\%D_P\). Simulations were performed using a scale resolved PANS approach, combined with cavitation modelling considering the fluid as a mixture and incorporating mass transfer source terms. The predicted impact on hull pressure is very large, with the maximum amplitude differing an order of magnitude between the small clearance case and the one with normal clearance. More important, however, is probably the forces exerted on the hull plate, and here the difference is much less; the standard deviation of pressure variation differs by a factor that does not exceed two. However, the higher order blade passing frequencies are much more prominent in the case with small clearance, presumably due to a complex behaviour of the tip vortex along the hull plate.

Keywords
Propeller cavitation, hull forces, hull pressure, PANS.

1 INTRODUCTION
For merchant ships, it is in general considered beneficial for propulsive efficiency to have as large diameter of the propeller as possible. The limitations are normally given by that the propeller tip should not extend below the keel line of the vessel, and that there is sufficient clearance between hull and propeller tip to have acceptable levels of pressure pulses and forces, thus not causing severe vibration problems inside the vessel. In the EU FP7 project STREAMLINE (grant no 233896), an ultra large diameter propeller was investigated to be placed aft of the transom of the vessel, with considerable gains in propulsive efficiency noted, in the order of 15\%. Currently, in the Horizon 2020 project LEANShips (grant no 636146) a propulsion system with a large propeller placed in normal position is investigated, but then with a tunnel design in the hull and a very small propeller tip clearance.

As part of the preliminary design studies, a sensitivity study regarding the effect on hull forces on propeller tip clearance has been performed. General empirical design knowledge has proven successful for standard clearance, say larger than 20\% of the propeller diameter, and current concept requires a much smaller clearance where little real life experience is available.

In this study, the preliminary ultra large diameter propeller, designed by Rolls-Royce, is simulated in a realistic wake flow below a generic hull plate with a tunnel, see Figure 1, where the vertical position of the hull plate is varied, from an extremely small value of below 1\% to the normally considered minimum of 20\% (of propeller diameter), with some values in between. Forces on the hull has been monitored together with pressure signal from an array of pressure probes on the hull plate. A representative operating condition was chosen, roughly corresponding to expected self-propulsion advance coefficient, where some cavitation is present on the blade in the top position.

Simulations have been performed in OpenFOAM using a PANS, Partially averaged Navier-Stokes, approach. Cavitation is modelled by a single fluid mixture approach, as e.g. reported in Bensow and Bark (2010). A sliding mesh approach is utilised for the propeller rotation, a challenge in itself in this configuration with a small tip clearance.

In the following sections, we first present the tested geometry and conditions, then describe the computational methodology and configuration. Among the results discussed, we present general propeller performance characteristics and flow behaviour, and the vertical forces on the hull plate as well as the pressure pulse characteristics. Focus is on the case with the small clearance, with references to the other tested configurations.

2 GEOMETRY AND CONDITIONS
The basis for this study is an early propeller design for the ultra large propeller and a generic hull plate, mimicking some features from the full hull aft-ship but constructed to allow for an easy translation in the vertical direction. For the full scale design, a propeller diameter of 7 \(m\) is considered with a tip clearance to the hull of only 5 \(cm\), corresponding to 0.7\(\%D_P\), where \(D_P\) is the propeller diameter. The generic hull plate was constructed with a tunnel of radius 1.4\(\%R_P\), with transversal extent of ±30\(^\circ\), and the hull outside the tunnel at further 30\(^\circ\) inclination. This hull plate was then shifted from the small clearance in vertical direction to 5\(\%D_P\) and 20\(\%D_P\), respectively, without changing the generic hull plate. We denote these three cases as Dp7, D5p, and D20p respectively, see Figure 1 for a visual representation of the propeller and hull plate.

The computational domain considered was a cylinder of radius 5\(D_P\), cut on the top by the generic hull plate, extended
about 6D_p downstream the propeller and about 1.5D_p upstream; see Figure 2. The shaft was put upstream the propeller and extended to the inlet.

Table 1: Cases considered for the study.

<table>
<thead>
<tr>
<th>Case</th>
<th>Clearance</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dp7</td>
<td>0.7%D_p</td>
<td>Small tip clearance, 0.7%D_p</td>
</tr>
<tr>
<td>Dp7S</td>
<td>0.7%D_p</td>
<td>Small tip clearance, 0.7%D_p, slip condition on hull plate</td>
</tr>
<tr>
<td>D5p</td>
<td>5%D_p</td>
<td>Intermediate tip clearance, 5%D_p</td>
</tr>
<tr>
<td>D20p</td>
<td>20%D_p</td>
<td>Normal tip clearance, 20%D_p</td>
</tr>
</tbody>
</table>

Figure 1: Illustrations of the propeller and generic hull plate for the three tip clearances considered.

It was desirable within the project working group to have as realistic conditions for the propeller as possible. It was thus decided to try to use the computed nominal wake from the hull as inflow condition to the simulations. This was not easily achieved, as the defined bilge vortices and vertical velocity component greatly deformed the wake before it reached the propeller. The tangential velocity components were thus somewhat reduced from the original nominal wake. Further, the nominal wake was computed for the small tip clearance, and an extension was necessary for the two cases with larger clearance. Some modifications where thus applied to the nominal wake, resulting in the inflow velocity field displayed in Figure 3 for the Dp7 case. The velocity deficit on the top was then extruded vertically as the hull plate was translated, leading to relatively similar wake conditions at the propeller plane. The free stream velocity is \( W_\infty = 1.395 \, \text{m/s} \).

The technique to generate the inflow was however not completely successful, with primarily two effects that influence the solution. The most severe one, was that the hull plate was represented by a no-slip wall condition, leading to a boundary layer development influencing the blade tip for the small clearance but not for the two with larger clearances. An additional case was thus set-up with a small clearance but with a slip condition on the hull plate to avoid the boundary layer build-up. This case is denoted Dp7S. Even then, the tangential velocity components were affected by the hull plate, leading to a slightly different wake fraction in the propeller plane, giving a somewhat different loading condition. This is most clearly seen through the variation in thrust between the conditions, see Table 4.

The rate of revolution was set to be the same for all conditions, with \( n = 5.39 \, \text{s}^{-1} \) to achieve the suitable advance coefficient. Cavitation number for the simulations was set to \( \sigma = 4.48 \), to mimic cavitation dynamics for the full scale vessel. As the large propeller is very lightly loaded, only a small sheet cavity at the tip occurs within the boundary layer for the small tip clearance cases, Dp7 and Dp7S. For the cases with larger clearance, the vapour volume at this cavitation number is almost negligible. Therefore, also a lower cavitation number was run for the D5p case, \( \sigma = 3.45 \), yielding approximately the same extent of the sheet cavity as in the Dp7 case. The results in terms of pressure pulses and hull forces did however not change.

Table 2: Cases considered for the study.

<table>
<thead>
<tr>
<th>Case</th>
<th>( D_p )</th>
<th>( \lambda )</th>
<th>( n )</th>
<th>( W_\infty )</th>
<th>( \sigma )</th>
<th>( \sigma_{alt} )</th>
</tr>
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<tbody>
<tr>
<td>Dp7</td>
<td>0.304 m</td>
<td>23</td>
<td>5.39</td>
<td>1.395 m/s</td>
<td>4.48</td>
<td>3.45</td>
</tr>
<tr>
<td>Dp7S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D5p</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D20p</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: The complete computational domain for the Dp7 case.

Figure 3: The inflow velocity conditions.

3 COMPUTATIONAL METHODOLOGY

The solver that is used is implemented using the open source software package OpenFOAM, which provides an object-oriented library, based on the finite-volume method,
specifically designed for CFD; see Weller et al. (1998) for a description of the structure of this software design.

The discretisation of the governing flow equations relies on storage of the unknown flow variables in the cell-center positions in the computational grid. The algorithm supports arbitrary polyhedral cells and the grid is treated as unstructured. The approximations involved are of second-order accuracy, except for flux limiting for the convective term, which reduces locally the formal order of accuracy near sharp gradients. The momentum equation is treated in a segregated manner, solving sequentially the three components of the momentum equations in a loop within each time step. This is done through a merged version of the SIMPLE (Patankar and Spalding, 1972) and PISO algorithms, where the PISO loop is complemented by an outer iteration loop and possible under-relaxation of the variables, called PIMPLE in OpenFOAM; see e.g. Barton (1998) for different ways to merge PISO and SIMPLE procedures. For the cavitating flow simulations, the mass transfer sources are computed first in the PISO loop, then the vapour fraction transport is progressed, and finally the standard PISO procedure is entered.

The simulations are time resolved and a second order backward differencing scheme is used for the time advancement of the components of the momentum equation. A domain decomposition technique, applied to the grid, in combination with an efficient MPI-implementation is used for running on parallel computers.

The inclusion of a moving component (in this case the propeller) is performed using the sliding-interface implementation in OpenFOAM. Interpolation is performed between the non-conforming interfaces between two regions, based on the interpolation algorithm by Farrell and Maddison (2011), denoted as AMI (Arbitrary Mesh Interface). This constitutes an efficient and conservative interpolation between non-conforming mesh interfaces based on Galerkin projection. The AMI has been shown to show good performance regarding both scalability and conservation of the flow quantities (Bensow, 2013; Turunen, 2014).

3.1 PANS

The partially-averaged Navier-Stokes, PANS, method is a bridging method between RANS and DNS, i.e. a modelling approach that seamlessly can be used through RANS to DNS, depending on mesh resolution and modelling parameters. Generally, bridging models are of particular interest in moderate grid resolutions where the cut-off is in the wave number range between RANS and LES. In these conditions, PANS has proven to provide better results compared to RANS, especially for dynamic flow conditions (Girimaji and Abdol-Hamid, 2005; Girimaji, 2006).

To achieve this, Girimaji (2006) proposed a generalized Boussinesq approximation for the sub filter scale tensor \( \tau_{ij} \),

\[
\tau_{ij} = -2\nu_u \rho_m \delta_{ij} + \frac{2}{3} k_u \rho_m \delta_{ij},
\]

where \( \delta_{ij} \) is the resolved rate of strain tensor,

\[
\delta_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right).
\]

The turbulent unresolved viscosity, \( \nu_u \), can be defined through the unresolved turbulent kinetic energy, \( K_u \), and the unresolved turbulent dissipation rate, \( \epsilon_u \), as,

\[
\nu_u = C_\mu \frac{(K_u)^2}{\epsilon_u}.
\]

Two parameters are introduced by Girimaji to create a correlation between fully averaged turbulence modelling (RANS) and partially averaged (PANS),

\[
f_k = \frac{K_u}{K},
\]

\[
f_\epsilon = \frac{\epsilon_u}{\epsilon}.
\]

These parameters represent the ratio of unresolved turbulent properties to the modelled ones. For instance, \( f_k = 1 \) means fully modelled turbulent kinetic energy, i.e. RANS, and \( f_k = 0 \) means fully resolved turbulent kinetic energy, which would correspond to DNS.

Different methods to define these parameters have been proposed, based on global or local grid properties. In this work, the simple static approach has been used by setting \( f_k = 0.7 \) and \( f_\epsilon = 1 \). This choice has been made on simple observations of the predicted flow using a range of parameters, also non-constant ones varying according to local cell size in relation to turbulent scales, based on predicted dynamics and computational stability.

3.2 Cavitation modelling

To simulate cavitating flows, the two phases, liquid and vapour, need to be represented in the problem, as well as the phase transition mechanism between the two. Here, we consider a one fluid, two-phase mixture approach, introduced through the local vapour volume fraction, \( \alpha_c \), and having the spatial and temporal variation of the vapour fraction described by a scalar transport equation including source terms for the mass transfer rate between the phases, \( \dot{m} \). The density \( \rho \) and dynamic viscosity \( \mu \) are assumed to vary linearly with the vapour fraction in the mixture,

\[
\rho = \alpha \rho_v + (1 - \alpha) \rho_l, \quad \mu = \alpha \mu_v + (1 - \alpha) \mu_l,
\]

with the bulk values, \( \rho_v, \rho_l, \mu_v, \) and \( \mu_l \), kept constant. Using this expression for the density in the continuity equation, it is straightforward to derive the non-homogeneous velocity divergence due to the mass transfer between the phases,

\[
\nabla \cdot \mathbf{v} = \left( \frac{1}{\rho_v} - \frac{1}{\rho_l} \right) \dot{m},
\]

that implies that the pressure correction equation in the segregated solver algorithm needs to be modified as well.

In the current study, the mass transfer model proposed by Sauer (2000) is employed,

\[
\dot{m} = \text{sign}(p - p_{th}) \frac{\alpha (1 - \alpha)}{R_B} \frac{3\rho_l}{\rho_v} \sqrt{\frac{2|p - p_{th}|}{3\rho_l}},
\]

where \( S_{ij} \) is the resolved rate of strain tensor,
where average nucleus per liquid volume is considered constant and in this study set to \( n_0 = 10^8 \), and the initial nucleus radius is \( d_{Nuc} = 10^{-4} \text{ m} \). Further, the modifications proposed by Asnaghi (2015) have been used, where the vaporisation component of Equation (7) is multiplied by a variable \( C_v \) based on local flow time scales,

\[
C_v = (1 + t_\infty |D|),
\]

and the local shear stress is considered in the pressure threshold,

\[
p_{th} = \mu \dot{\gamma} + p_{Sat}, \quad \mu \dot{\gamma} = \sqrt{D_\perp D}.
\]

### 3.3 Computational configuration

All results presented below, have been run using the methodology described above. To initiate the flow, first, the Dp20 simulation was run using RANS with large time step in non-cavitating conditions until a well developed flow was achieved. Then, a set of simulations using different \( f_k \), ranging between 0.1 and 0.9, as well as model with locally varying \( f_k \), to determine appropriate parameter setting; here we settled on using \( f_k = 0.7 \). After letting the flow develop the smaller structures allowed by the PANS, cavitation was initiated, and the simulation was allowed to run for some further propeller revolutions before pressure probe and force sampling was initiated. For the other cases, the fully developed solution of the Dp20 simulation was mapped to the smaller domains, and the flow was again allowed to develop.

For the convective terms, a TVD limited scheme was used for the momentum terms and upwind for the turbulent transport, and time stepping was performed with an implicit second order scheme. The time step in the runs where results were collected, was set to \( 1/10 \) of a degree of propeller revolution, which results in \( \Delta t = 5.1536 \cdot 10^{-5} \text{ s} \).

The meshes were generated in Pointwise® in three regions. First, a cylindrical puck enclosing the propeller was created for the rotating region; the radius of this cylinder was chosen to leave only a single cell layer between the cylinder and the hull tunnel for the case with the small clearance. Here, an unstructured quad dominant mesh was created on the surface of the propeller blades, hub, and the enclosing cylinder, then extruding a hex dominant boundary layer mesh, and finally filling the puck domain with unstructured tetrahedral cells using the anisotropic mesh extrusion feature of Pointwise®, T-Rex; see Figure 4. Around this puck, and for the extent of the generic hull, a structured hex mesh was created, in order to transport the inflow conditions to the propeller and the propeller slip downstream. Finally, for the downstream part and the outer perimeters of the large cylinder domain a general unstructured coarse mesh was created. The cell distribution for the Dp7 configuration is given in Table 4; for the cases with larger tip clearance, a additional structured hex block was introduced. On the propeller surface, we measure \( y^+ \) values in the range of 0.5 - 15, with a typical value \( y^+ \approx 5 \).

<table>
<thead>
<tr>
<th>#cells/10^6</th>
<th>Domain</th>
<th>Propeller</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hex</td>
<td>3.8</td>
<td>4.3</td>
<td>8.1</td>
</tr>
<tr>
<td>Tet</td>
<td>2.5</td>
<td>3.0</td>
<td>5.5</td>
</tr>
<tr>
<td>Prism</td>
<td>0.1</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Pyramids</td>
<td>-</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td>6.4</td>
<td>9.0</td>
<td>15.4</td>
</tr>
</tbody>
</table>

Figure 4: Display of the computational mesh for the small clearance case; the propeller mesh is the same for all cases.
4 RESULTS

The main underlying concern for this study was to get better understanding of how a small tip clearance for this large, lightly loaded propeller would affect the risk of vibrational problems on the vessel. Current design experiences and rules of thumb do not extend to this configuration. The main focus was thus to monitor vertical force on the generic hull plate and pressure on an array of probes mounted on the hull plate just above the propeller. The following discussion mainly follows this, and only presents results regarding propeller performance and flow development to support the objective.

4.1 Data acquisition

As mentioned above, an array of probes to measure the pressure was created on the tunnel boundary patch, as displayed in Figure 5a. In total, 55 probes were used, placed in five lines along the flow direction with 11 probes in each line spanning the tunnel. These are denoted with a three digit combination, where the first indicate the row, and the next two the position along its row with the ascending number following the blade rotational direction; some of the probes are annotated in Figure 5a to exemplify this. The second line, probes 201-211, is located at the propeller axial centre position, giving then that the third line, probes 301-311, is located more or less at the axial position of the smallest clearance (due to the propeller skew).

Forces were monitored on three separate boundary patches, indicated by different colours in Figure 5b. One patch just above the propeller and extending a short distance downstream, one for the rest of the tunnel, and one for the rest of the hull plate. However, in the results section, only the total force on these three patches has been used in the analyses as it’s most representative for the situation that needs to be considered for the full ship.

4.2 General flow behaviour

In Table 4, the measured thrust and torque coefficients are listed for the four conditions. The thrust for the case with the large clearance, D20p, is approximately 6% higher than the cases with low clearance, and the torque about 3% higher. The reason for this difference may be attributed to two things. The first is that the wake has developed somewhat differently from the inflow to the propeller plane, due to the specified in-plane velocity components developing differently in the three geometrical configurations. The second would be that the proximity of the hull plate directly influence the flow development and the pressure field around the propeller. It has not been possible within the scope of this study, to adjust conditions in any way to achieve thrust identity.

Table 4: Propeller performance

<table>
<thead>
<tr>
<th></th>
<th>Dp7</th>
<th>Dp7S</th>
<th>D5p</th>
<th>D20p</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_T$</td>
<td>0.158</td>
<td>0.157</td>
<td>0.160</td>
<td>0.168</td>
</tr>
<tr>
<td>$K_Q$</td>
<td>0.0263</td>
<td>0.0262</td>
<td>0.0266</td>
<td>0.0273</td>
</tr>
</tbody>
</table>

Cavitation development for the Dp7 case is shown in Figure 6, where maximum cavity volume is displayed in Figure 6c. Cavity extent is similar for the small clearance, slip condition case Dp7S. As commented above, for the same cavitation number, $\sigma = 4.48$, the cases with larger clearance hardly cavitated at all. With the reduced cavitation number, $\sigma = 3.45$, as tested for the D5p case, similar cavity extent was achieved. Mesh resolution was not high enough to allow for a cavitating tip vortex, naturally in combination with the lightly loaded propeller in itself. The visualised behaviour is fully expected.

Further, looking at the tip vortex development, Figure 7, an interesting dynamics is noted for the tip vortex operating in the boundary layer of the hull plate in Dp7. Starting with Figure 7a, displaying the case with normal clearance, we see a tip vortex following the propeller pitch, more or less, as we’re used to. Turning instead to Figure 7c, we note two interesting effects. The first, and most obvious, is that on the edge of the tunnel, the tip vortex from the blade preceding the top blade is divided, with one part being linked up-streams towards the top blade and the other part being somewhat dislocated downstream. The second, more subtle effect, but presumably of the same origin, is that the tip vortex from the top blade is also dislocated upstream compared with the blade wake from the same blade. To complete the picture, also the Dp7S case, with small clearance without the boundary layer, is displayed in Figure 7b.
Here, we see a tendency to the up-stream dislocation of the tip vortex, but it's significantly weaker, and the downstream vortices are not split. The proximity to the hull thus has some effect to induce this behaviour, but the main component is some interaction between the tip vortex and the boundary layer. This, naturally, has a large impact on the frequency content of the forces and pressures measured on the hull, as is discussed below. We remark also, that would the tip vortex cavitate, this impact would be expected to be even larger.

4.3 Hull pressure

Here, for the sake of brevity, we only consider the case with small clearance, Dp7. The maximum amplitude in this configuration is much higher than the others, $p_{\text{max},Dp7} \approx 2.5 \ kPa$, while $p_{\text{max},Dp7S} \approx 1.0 \ kPa$, $p_{\text{max},Dp20} \approx 0.5 \ kPa$, and $p_{\text{max},Dp20p} \approx 0.1 \ kPa$. Note that these values are for a model scale set-up. It is interesting to note that it’s not only the distance between the blade tip and the hull plate that influences the amplitude, but that the presence of the boundary layer, and thus presumably the tip loading, has a large impact.

The signal sampled along two directions is plotted in Figure 9. The first frame, Figure 9a, corresponds to the probes along the hull centre line, starting with the probe at the propeller axial centre position (206) and moving aft (306, 406, 506) with pressure plotted against blade position. Here, also the cavity volume is indicated on the right axis. The second frame, Figure 9b, instead corresponds to three probes at the same axial position, passed by the blade tip: one at the centre of the tunnel (306), and two closest to the tunnel edges (301, 311).

We find here two things to mention. The first is that the maximum pressure occurs during cavity growth, just before maximum cavity volume is reached. The second, and more unexpected, is that for the more upstream probe, 206, the signal is out of phase with the others. The reason for this is once again the dislocation of the tip vortex in the boundary layer, as noted above, and the peak for 206 occurring at $-30^\circ$ comes from the passage of the tip vortex of the preceding blade.

4.4 Hull forces

Turning to the force measured on the hull, the total force and its spectral content is plotted in Figure 8 for Dp7 and D20p. The average force for these two conditions, is almost the same, $<F_y> \approx 67.3 \ N$ for Dp7 and $<F_y> \approx 67.0 \ N$ for Dp20. Using the standard deviation as a measure of the force variation, we note that for Dp7, $\sigma(F_y) = 1.04$, and for D20p, $\sigma(F_y) = 0.53$; thus almost the double for the small clearance. It is also clear, looking at the time trace of the forces in Figures 8a and 8c, that the behaviour is quite different, attributed primarily to the vortex development noted above, but cavity dynamics might contribute as well. We remark that the high frequency noise is believed to be numerically related.

To look further into this difference, a spectral analysis was performed. As the simulations were not run long enough for a reliable Fourier analysis, the signals in Figures 8a and 8c were periodically extended and the FFT was performed on the extended signal. Comparing signals sampled during different propeller rotations do not reveal any major unsteadiness, and thereby the procedure is reasonable, at least for a qualitative analysis. The resulting spectrum is shown in Figures 8b and 8d for the two cases, respectively.

Figure 6: Cavity development during one blade passage. The blade is shaded with surface pressure.
from the higher peak for Dp7 at the first BPF, blade passing frequency, compared with D20p, the presence of significant components of 2 BPF up to 8 BPF, is a strong indication of the complex behaviour of the case with small clearance. As a comparison, the normal clearance case show contribution only from 3 BPF and 4 BPF.

5 CONCLUDING REMARKS

The objective of this study was to investigate how hull forces and pressure is influenced by small propeller tip clearance by creating a set-up where systematic variation of tip clearance could be achieved at similar propeller conditions; in this study, clearances between the propeller tip and a generic hull with tunnel configuration were 0.7\%Dp, 5\%Dp, and 20\%Dp. This turned out to be a challenging task, as it was preferred to have the propeller operating in a realistic ship wake, and this wake flow is influenced by the geometric features of the configuration. The conditions are thus not identical during the variation, but deemed similar enough to generate some interesting knowledge.

The impact on hull pressure is very large, with the maximum amplitude differing an order of magnitude between the small clearance case and the one with normal clearance. More important, however, is probably the forces exerted on the hull plate, and here the difference is much less; the standard deviation of pressure variation differs by a factor that does not exceed two. However, the higher order blade passing frequencies are much more prominent in the case with small clearance, presumably due to a complex behaviour of the tip vortex along the hull plate.

To get a more direct understanding of the risk for vibrational issues for a vessel like this, with a large diameter, lightly loaded propeller with a small tip clearance, the complete configuration, with the propeller operating behind the full hull, is currently being investigated using RANS and PANS simulation methodologies.

ACKNOWLEDGEMENTS

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REFERENCES


Figure 8: Total force on the hull plate during one revolution, and the associated spectrum, for the case with small and regular tip clearance, respectively.

Figure 9: Pressure signals on hull.
DISCUSSION

Questions from Casey Harwood, The University of Iowa

I wish to commend the authors for a very interesting paper. The authors have very satisfactorily addressed the effects of small tip clearance upon the vertical excitation force on the hull panel, but I think that consideration should be given to the blade loading as well. Small tip clearances reduce the strength of tip vortices, thus increasing the bound circulation near the tip of the blade. My concern is that an ultra-small tip clearance would induce a large periodic fluctuation in the loading and root bending moment of each blade as it passes the 12 o'clock position, with a consequential vertical bending moment on the propeller shaft. Do the authors have any plans to assess the blade loading?

The interaction between the tip vortex and wall boundary layers in ducted propellers can lead to complex vortex-vortex interactions, with the result that minimum vortex core pressures and cavitation inception occur downstream of the blade trailing edge. Can the authors comment upon the possibility of cavitation noise induced by limited tip vortex cavitation?

Author's closure

We have up to now not considered implications on the bending moment of the blade. It is indeed a very interesting point that we have overlooked. We will definitely extend the analysis to include these aspects. Unfortunately, there is not sufficient data saved from the simulations to extract this sufficiently well from the simulations already done so we cannot give any indication in this discussion; new runs are needed.

The resolution of the simulations is not such that tip vortex cavitation can be captured, but can clearly be expected in reality. This will surely induce both pressure pulses and noise, and in particular be expected to induce energy in the higher blade passing frequency harmonics. With the larger propeller, the blade loading overall, and especially in the tip, can be reduced, thus also the amount of tip vortex cavitation can be expected to be smaller than for a propeller with ordinary diameter. We thus think the lower harmonics will still be the major impact factor on the structural design. This situation might then be different if a regular propeller is used with a small tip clearance.