Analysis of the influence of an upstream rudder over the wake features of a submarine propeller

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ABSTRACT

Large-Eddy Simulation is utilized to analyze the effect of an upstream rudder on the wake features of a submarine propeller. Three incidence conditions of the rudder, relative to the free-stream, are considered. Results are also compared with those of earlier similar computations in open-water conditions. The overall approach on the same propeller was validated by an earlier study on the open-water configuration and the same advance coefficient, via comparisons with Particle Image Velocimetry experiments of the wake flow and dynamometric measurements on the parameters of global performance. Results reported in this work demonstrate that the disturbance at the inflow of the propeller does not change substantially the topology of the largest coherent structures within the near wake (the tip and hub vortices). In addition, as long as the flow over the rudder keeps attached, the levels of fluctuations downstream of the propeller are only slightly increased and thus the perturbation of the inflow keeps small. However, at the largest simulated incidence condition the separation occurring over the suction side of the hydrofoil causes instead more substantial changes in wake turbulence, although also in that case the near wake coherence of tip and hub vortices is almost unchanged. At the same condition, downstream of the instability of the wake system, the interaction with the vortices shed from the ends of the hydrofoil further increases the unsteady nature of the wake flow and the extent of the flow region affected by large values of turbulent fluctuations.

Keywords

Submarine Propellers, Rudder-Propeller Interaction, Large-Eddy Simulation, Coherent Structures.

1 INTRODUCTION

Submarine propellers operate in the wake of upstream rudders. Especially in maneuvering conditions the rudders generate a disturbance on the flow ingested by the propeller. This affects the propeller load and influences the properties of stability of the complex wake system. Although a few high-fidelity computational studies are already available in the literature, highlighting the wake features of submarine propellers in open-water conditions (Balaras et al 2015, Kumar & Mahesh 2017), similar eddy-resolving studies on rudder-propeller interactions and the resulting wake structure are limited. Schroeder et al (2014), for example, reported large-eddy simulations (LES) of the INSEAN E1619 propeller downstream of a rudder, but the limited computational resources allowed analyzing only one configuration at 0 yaw angle. In such condition the perturbation produced by the upstream hydrofoil was mild and did not have a significant impact on the wake features, compared to the open-water configuration. In addition, a few LES simulations dealing with a submarine propeller operating in the wake of hull/rudders are already available in the literature (see, for instance, Alin et al 2010, Petterson et al 2018 and Posa & Balaras 2018). However, in those cases the focus is on the overall submarine body, rather than on the rudder/propeller system and propeller wake instabilities. Therefore, computational resources are distributed across the whole domain, rather than being clustered in the vicinity of rudders and propeller, to capture the detailed flow structures resulting from their interaction.

In the present study we aim at assessing the influence of an upstream rudder, modeled via a NACA0020 hydrofoil, on the INSEAN E1658 propeller. This submarine propeller is a modification of the INSEAN E1619. Our LES computations of the INSEAN E1658 propeller in open-water conditions (Posa et al 2018, Posa et al 2019) are in excellent agreement with the corresponding PIV measurements by Felli & Falchi (2018). This paper is organized as follows: in Sec. 2 the methodology is shortly discussed, in Sec. 3 the computational setup is reported and in Sec. 4 results are provided, including comparisons of the configurations with upstream disturbance with the computations carried out in open-water conditions. Conclusions are given in Sec. 5.

2 METHODOLOGY

Simulations of the flow were carried out via solution of the filtered Navier-Stokes equations in non-dimensional form:

\begin{equation}
\nabla \cdot \tilde{\mathbf{u}} = 0,
\end{equation}

\begin{equation}
\frac{\partial \tilde{\mathbf{u}}}{\partial t} + \nabla \cdot \tilde{\mathbf{u}} \tilde{\mathbf{u}} = -\nabla \tilde{p} - \nabla \cdot \mathbf{\tau} + \frac{1}{Re} \nabla^2 \tilde{\mathbf{u}} + \mathbf{f},
\end{equation}

where the size of the filter was defined by the spacing of the adopted computational grid. In the above equations \( \tilde{\mathbf{u}} \) and \( \tilde{p} \) are the filtered velocity vector and the filtered pressure, respectively, \( t \) is the time variable and \( Re \) is the
Reynolds number, defined as \( Re = U L / \nu \), with \( U \) reference velocity, \( L \) reference length and \( \nu \) the fluid kinematic viscosity. In the present case \( U \) and \( L \) were selected as the free-stream velocity, \( U_\infty \), and the propeller diameter, \( D \). The tensor \( \tau \) comes from filtering the Navier-Stokes equations and includes the effect of the scales smaller than the grid spacing on the resolved scales. It needs to be parameterized via a subgrid scale (SGS) model. In this case the wall-adapting local eddy-viscosity model developed by Nicoud & Ducros (1999) was utilized, as for the open-water computations validated in our earlier works (Posa et al 2018, Posa et al 2019). In Eq. 2 the last term, \( f \), was utilized to enforce the no-slip boundary conditions on the surface of solid bodies, via an immersed-boundary approach. This allowed us to utilize a cylindrical Eulerian grid, not required to conform to the geometries of both upstream rudder and downstream propeller, whose surfaces were approximated by means of triangulated Lagrangian grids, free to move across the Eulerian grid. More details on the immersed-boundary methodology utilized in the present study are reported by Yang & Balaras (2006). Applications of the same solver to engineering flow problems can be found in Posa (2019) and Posa & Lippolis (2019).

Discretization in space of the Navier-Stokes equations was carried out using second-order central finite-differences on a staggered cylindrical grid. Advancement in time utilized an exact projection method (Van Kan 1986). Discretization in time of the convective, viscous and SGS terms of azimuthal derivative utilized the implicit Crank-Nicolson scheme, while all terms of radial and axial derivatives were approximated explicitly via the three-steps Runge-Kutta scheme. The pressure gradient term was computed also explicitly, using its value at the last time level. The solution of the Poisson problem stemming from Eq. 1 was achieved using FFT along the azimuthal direction, reducing the overall pentadiagonal system of equations to a pentadiagonal system per each azimuthal slice of the cylindrical grid, resolved by means of a direct solver (Rossi & Toivanen 1999).

3 COMPUTATIONAL SETUP

Three configurations will be analyzed, with the upstream hydrofoil at incidence angles of 0 deg, 10 deg and 20 deg, relative to the free-stream, producing an increasingly stronger disturbance to the flow ingested by the propeller. For brevity, they will be indicated as conditions \( C00 \), \( C10 \) and \( C20 \). The open-water configuration, whose results are reported in our earlier works (Posa et al 2018, Posa et al 2019) and taken as reference in some cases, will be indicated as \( COW \). However, it is worth noting that results for \( C00 \) were found very similar to those for \( COW \).

The location of the hydrofoil upstream of the propeller, as well as its chord, relative to the propeller diameter, were selected based on the geometric features of the fins of the DARPA suboff (Groves et al 1989), assuming a propeller diameter equal to half the cylindrical mid body of the submarine model. To generate the three simulated configurations the NACA0020 hydrofoil was rotated relative to its mid chord location. The overall system is shown in Fig. 1 for a 0 deg yaw angle of the rudder, whose spanwise dimension is aligned with the direction of the \( y \) axis of the frame of reference.

The Eulerian grid utilized in the present study is cylindrical and the Lagrangian grids, representing the surfaces of rudder and propeller, are immersed within the Eulerian grid. The Eulerian grid is composed of 1.7 billion nodes (800 \( \times \) 1026 \( \times \) 2050) along the radial, azimuthal and streamwise directions, respectively, whereas the Lagrangian grids consist of about 80,000 and 160,000 triangular elements for the rudder and propeller geometries, respectively. Note that those grids were designed to have the same resolution as that utilized for the simulation of the INSEAN E1658 propeller in open-water conditions (Posa et al 2018, Posa et al 2019), extending also the size of the computational domain in the region upstream of the propeller, to accommodate the hydrofoil. However, compared to the simulations carried out in open-water conditions, the resolution of the computational grid was improved upstream of the propeller, in order to resolve the flow over the hydrofoil. The computational setup is shown in Fig. 2, where the NACA0020 profile is oriented at an
incidence angle relative to the free-stream equal to 20 deg. The inflow, outflow and lateral boundaries of the computational domain were all placed at 5D away from the center of the propeller disk, where also the origin of the reference frame was located. All coordinates in the following discussion on the wake features will be based on this choice. Uniform velocity, convective and slip-wall with impermeability conditions were enforced at the inflow, outflow and later boundaries of the computational domain. The size of the rudder along the spanwise direction (2 propeller diameters) is again based on the geometry of the DARPA suboff body and was designed to avoid that its tip vortices are ingested by the propeller. The advance coefficient, $J = V/nD$, simulated in the framework of the present study, is $J = 0.65$, where $V = U_\infty$ is the advance velocity, equal to the free-stream velocity, $n$ the propeller rotational speed and $D$ the propeller diameter. The Reynolds number, based on the chord of the propeller blades and the relative velocity of the free-stream at 70% of their radius, is about $Re \cong 310,000$.

**Figure 3:** Instantaneous isosurfaces of pressure for the configurations C00 (a), C10 (b) and C20 (c). Visualization of the tip vortices. For clarity, the flow field at inner radii was blanked out.

**Figure 4:** Instantaneous isosurfaces of pressure for the configurations C00 (a), C10 (b) and C20 (c). Visualization of the hub vortex.

**4 RESULTS**

An overview of the flow downstream of the propeller for all three simulated configurations is reported in Fig. 3, where isosurfaces of pressure from instantaneous realizations of the flow were utilized to extract information about coherent structures. For clarity, the flow field upstream of the propeller plane and at inner radii was blanked out, in order for the tip vortices to be better distinguishable. It is interesting to see at outer radii in Fig. 3b and especially in Fig. 3c the structures coming from the ends of the upstream hydrofoil, associated to the pressure gradient generated between pressure and suction sides at non-zero incidence, relative to the free-stream. Within the near wake, up to development of instability at about one propeller diameter downstream, the evolution of the tip vortices is rather similar for all three angles of attack of the rudder. We will show later that also the phase-averaged fields demonstrate that the propeller tip vortices keep coherent over similar downstream distances.
More detailed comparisons across all simulated cases will be presented in the following, looking at the statistics of the wake flow, where differences across the three simulated cases become more distinguishable. Phase-averages were computed using only instantaneous realizations of the flow relative to a particular position of the propeller blades. Thus, they are synchronized with the propeller rotation. About 200 instantaneous solutions were utilized to compute the statistics dealing with each case. In Fig. 5 phase-averaged contours of streamwise velocity are shown over the $y = 0$ plane, orthogonal to the axis of the rudder. The propeller wake features a region of accelerated flow, across the radial extent of its blades, and a minimum of streamwise momentum at the wake axis, due to the large hub vortex visualized in Fig. 4. From Fig. 5a to Fig. 5c the deflection of the wake axis is very obvious, as well as an increasing asymmetry of the distribution of streamwise momentum within the wake across its radius. This result is shown more quantitatively in Fig. 6, where ensemble-averaged cross-stream profiles are shown in the same plane $y = 0$ as in Fig. 5, normal to the axis of the hydrofoil, at the streamwise location $z/D = 3.0$. Ensemble-averages are a global average, including all available instantaneous realizations of the flow during the computation and thus all positions of the propeller blades. In addition, in Fig. 6 also the case COW is considered. It is interesting to see in Fig. 6 that the case C00 practically overlaps with COW (Posa et al. 2018, Posa et al. 2019), confirming our earlier finding that in such condition the inflow perturbation is too weak to produce negligible effects on first-order statistics of the wake flow (Balaras et al. 2015). However, as seen in Fig. 5, increasing levels of wake deflection and asymmetry are produced by an increasing angle of attack of the upstream rudder, with also a readjustment of momentum distribution across the propeller wake.

Figure 5: Phase-averaged contours of streamwise velocity over the $y = 0$ plane for the configurations C00 (a), C10 (b) and C20 (c). Streamwise velocity scaled by $U_\infty$.

Instantaneous visualizations of the hub vortex are shown in Fig. 4, again via isosurfaces of pressure. Also in this case the flow field upstream of the propeller plane was blanked out, for visual clarity. Due to the deflection of the flow ingested by the propeller by the upstream rudder, the axis of the propeller wake experiences a deflection as well, increasing from Fig. 4a to Fig. 4c. The size of the hub vortex is larger than that of the tip vortices and not much dependent on the perturbation of the inflow generated by the upstream hydrofoil at incidence. Also in this case, the qualitative visualization of the wake provided in Fig. 4 does not point to substantial effects on the topology of the coherent structures by the upstream disturbance: the hub vortex, as the tip vortices, is a structure much stronger, compared to those shed by the hydrofoil and ingested by the downstream propeller, even at large values of incidence. Also in Fig. 4c at more downstream locations the interaction of the propeller wake with the rudder tip vortices is distinguishable, with structures elongated from the wake core towards outer radii.

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Figure 6: Cross-stream profiles of ensemble-averaged streamwise velocity over the $y = 0$ plane at $z/D = 3.0$. Profiles refer to configurations: COW (solid line), C00 (dotted line), C10 (short-dashed line) and C20 (long-dashed line).

Fig. 7 shows the phase-averaged fields of turbulent kinetic energy over the plane $x = 0$, aligned with the axis at the mid-chord of the rudder. Isolines of pressure are shown on top of the contours. Results in Fig. 7a and Fig. 7b, dealing with cases C00 and C10, are similar to those we reported for the configuration COW (Posa et al. 2018, Posa et al. 2019), with slightly higher val-
ues within the wake of each propeller blade, the tip and especially the hub vortices, as a consequence of the inflow disturbance generated by the hydrofoil. Some differences are distinguishable between Fig. 7a and Fig. 7b. In the latter case we can see that values of turbulent kinetic energy for negative y coordinates are higher than those for positive y coordinates, especially within the tip vortices, whereas contours in Fig. 7a are more symmetric (the asymmetry is only due to the propeller geometry). This result for C10 is tied to the deflection of the upstream disturbance. The structures on the top part of Fig. 7b are about to enter the region affected by the wake of the rudder, which is displaced towards positive x coordinates (the direction inwards the plane of Fig. 7), whereas those in the bottom part of Fig. 7b just went through that region, increasing the level of turbulent fluctuations within the wake of the propeller blades. The hub vortex correlates with a wide region of low pressure at the wake axis, as shown by the isolines. The tip vortices at the outer radii keep very well distinguishable up to about one propeller diameter downstream, where the interaction with the hub vortex becomes significant. Local maxima of turbulent kinetic energy correlate with the position of both hub and tip vortices, identified via pressure isolines. Flow fields are dramatically modified in Fig. 7c, dealing with the case C20, with a substantial increase of turbulent kinetic energy across all radii. This behavior was verified associated to separation phenomena occurring over the suction side of the rudder. Indeed the upstream region of Fig. 7c shows that turbulence ingested by the propeller is an order of magnitude higher than that seen in both Fig. 7a and Fig. 7b, due to separation and production of a much wider wake. However, it is worth noting that the distribution of the phase-averaged pressure isolines, tied to the hub and tip vortices in the wake, is not drastically modified as well, confirming the result from the instantaneous fields above. They suggest that separation over the surface of the rudder has a strong effect on turbulent fluctuations, but less significant consequences on the coherence of the largest structures of the propeller wake (hub and tip vor-
Separation over the suction side of the rudder is the source of the dramatic change in turbulent kinetic energy seen in Fig. 7c, compared to cases C00 and C10. Phase-averaged contours of azimuthal vorticity over the $y = 0$ plane are reported in Fig. 8, which allows us to highlight the separation occurring at the configuration C20. Note that the azimuthal component of vorticity switches its sign at the axis of the computational grid. Fig. 8a and Fig. 8b show that the boundary layer over the hydrofoil keeps attached, whereas this is not the case for the configuration with the largest incidence in Fig. 8c. A large shear layer is shed from the leading edge of the rudder on the side of the adverse pressure gradient and the area of large vorticity and turbulence ingested by the propeller is significantly wider than those visualized in both Fig. 8a and Fig. 8b. Actually, we can see in Fig. 8c that the impact of such phenomenon on the phase-averaged fields of vorticity downstream of the propeller disk is not substantial, confirming that the topology of the propeller wake is practically not modified, but we have demonstrated above that wake turbulence is strongly enhanced in the case C20.

Results at $z/D = 0.5$ downstream of the propeller plane are shown in Fig. 9b. They are very interesting, since they point to the actual influence of the upstream rudder on overall turbulence within the propeller wake. Values for C00 and C10 are practically identical to those in open-water conditions at intermediate radii. The maxima at outer radii, associated with the tip vortices, and at the wake axis, associated with the hub vortex, are an exception, since ensemble-averaged turbulence there grows, compared to COW. We verified that actually the overall influence of the upstream disturbance on phase-averaged turbulent kinetic energy within the tip vortices is small across the whole azimuthal extent of the propeller wake. Therefore, the result shown in Fig. 9b suggests that the increase of ensemble-averaged turbulence is due to higher velocity fluctuations within those coherent structures only when they go through the flow region directly affected by the wake of the upstream rudder. This hypothesis is reinforced by the higher values of the outer maxima for negative $y$ coordinates in the configuration C10. As noticed with reference to Fig. 7b, this asymmetry is caused by the displacement of the rudder wake towards the region of positive $x$ coordinates. On the side of positive $y$ coordinates the tip vortices are about to enter the flow region affected by the upstream disturbance, while on the opposite side they are just exiting the same flow region and experience a local increase of velocity fluctuations, as a consequence of the interaction with the inflow perturbation. Obviously, the case C20 displays the most significant changes. Also for this configuration the distribution is not symmetric, with larger values for negative $y$ coordinates, although a substantial increase, relative to the reference configuration, is evident across the whole propeller wake. Also the maxima associated with tip and hub vortices experience an increase. We verified such increase also from the phase-averaged turbulence within the core of those structures. Smaller maxima outside of the turbulent kinetic energy are reported over the $x = 0$ plane, through the axis of the hydrofoil. Also the results for the case COW are provided in Fig. 9. Profiles in Fig. 9a refer to the streamwise location at $z/D = -0.1$, immediately upstream of the propeller plane. Note that they go through the hub at inner radii, where values are obviously equal to 0. For the case with no rudder, small velocity fluctuations are tied to the periodic passage of the propeller blades, rather than to actual turbulence. While profiles for C00 and C10 show similar levels of turbulent kinetic energy ingested by the propeller, for C20 a significant increase is visible, which is not symmetric relative to the propeller axis, with higher values for positive $y$ coordinates, as also seen above in Fig. 7. Such asymmetry is due to the suction produced by the propeller. The highest values occur at the radii where the propeller causes the strongest suction effects. Additional turbulence peaks at outer radii are associated with the vortices originating from the rudder tips. In Fig. 9a it is evident that the separation occurring over the suction side of the rudder is source of levels of turbulence ingested by the propeller an order of magnitude higher than those observed also in the presence of the upstream rudder, but with no separation of its boundary layer.

A more quantitative comparison across cases is presented in Fig. 9, where cross-stream profiles of ensemble-averaged turbulent kinetic energy are reported over the $x = 0$ plane, through the axis of the hydrofoil.

**Figure 9:** Cross-stream profiles of ensemble-averaged turbulent kinetic energy over the $x = 0$ plane at $z/D = -0.1$ (a) and $z/D = 0.5$ (b). Profiles refer to configurations: COW (solid line), C00 (dotted line), C10 (short-dashed line) and C20 (long-dashed line).
propeller wake for cases C10 and C20 are located within the core of the tip vortices produced by the upstream rudder. For both cases at $z/D = 0.5$ they do not play a significant role in affecting turbulence within the propeller wake. We have indeed seen in Fig. 3 that at the considered streamwise location they are actually still separated from the wake system of the propeller.

In Fig. 10 the same streamwise position as in Fig. 9b is considered, but over the $y = 0$ plane. Interestingly, the cross-stream profiles in Fig. 10 demonstrate little influence of the upstream rudder on ensemble-averaged turbulence at outer radii, even in the case at the largest incidence. As long as the tip vortices keep stable, up to about $z/D = 1.0$, levels of turbulence at azimuthal locations away from the wake of the hydrofoil are not substantially increased from the reference open-water configuration. Compared to the results seen in Fig. 9b, one can infer that in the near wake the upstream rudder introduces a perturbation increasing the fluctuations of the tip vortices, but this effect does not propagate when they move to azimuthal coordinates away from the wake of the hydrofoil. Note that in Fig. 10, while at the outer radii all cases practically overlap each other, since they are outside of the flow region affected by the hydrofoil, the computation for the strongest perturbation shows an obvious increase of fluctuations within the wake core, influencing especially the hub vortex. Such increase is asymmetric, with a displacement of the central peak towards positive $x$-coordinates, due to wake deflection. It is also worth noting that such peak is much higher than that seen in Fig. 9b. In Fig. 9b the cross-stream profile is indeed displaced away from the core of the hub vortex, in contrast to that shown in Fig. 10.

Cross-stream profiles at a location further away from the propeller ($z/D = 2.0$), downstream of the instability of the tip vortices, are presented in Fig. 11, again over the $x = 0$ plane (a) and the $y = 0$ plane (b), respectively. In Fig. 11a turbulence distribution across the wake for cases C00 and C10 is again similar to that for COW. Also differences at outer radii are rather small. This is not the case at the largest incidence. It is also likely that for C20 the interaction with the vortices originating from the rudder tips contributes to higher levels of fluctuations, especially at outer radii. Whereas the case C10 displays two small bumps on both sides of the propeller wake ($y/D = \pm 0.9$), tied to the tip vortices from the upstream hydrofoil, they are not distinguishable within the profile relative to C20. They are likely merged to turbulence in the outer region of the propeller wake. Those additional structures are therefore contributing to a stronger destabilization of the propeller wake and to increase turbulent fluctuations. This result is confirmed in Fig. 11b. In contrast with the upstream location considered in Fig. 10, where higher fluctuations occurred only within the wake core, profiles in Fig. 11b show for C20 an increase across all radii, in comparison with the open-water distribution. The stronger instability of the wake system for case C20, involving also the large coherent structures coming from the tails of the rudder, leads to higher levels of turbulent kinetic energy across the whole azimuthal extent of the wake, compared to all other considered configurations. We can see indeed that their cross-stream profiles in Fig. 11b are almost identical, besides the displacement of that for C10, due to wake deflection, from those relative to COW and C00.

5 CONCLUSIONS

A Large-Eddy Simulation approach was utilized to investigate the influence of an upstream rudder on the wake features of a submarine propeller. Three yaw conditions of the rudder were considered, equivalent to angles of...
attack, relative to the free-stream, of 0 deg, 10 deg and 20 deg. Comparisons were presented across the three simulated configurations and with the open-water case, studied in earlier works by the same authors (Posa et al 2018, Posa et al 2019), where the overall approach was also validated via comparisons with measurements within the propeller wake by Felli & Falchi (2018).

Present results demonstrated that, even in the presence of the strongest simulated inflow perturbation, the topology of the near wake is not substantially modified. It is dominated by tip and hub vortices, whose size and stability are not much dependent on the upstream perturbation, likely because they are much stronger than any structure within the wake of the upstream hydrofoil, even when its boundary layer experiences separation. In contrast, turbulent fluctuations within the propeller wake are affected by the inflow conditions. Actually, with the rudder at incidences of 0 deg and 10 deg the effect on turbulent kinetic energy is rather mild and limited to the azimuthal coordinates directly downstream of the hydrofoil. This result indicates that fluctuations are increased only locally, but interaction with the wake of the rudder is not able to trigger a global destabilization of the wake system. This was found not the case at an incidence of 20 deg. Separation of the boundary layer over the suction side of the rudder produces a much wider wake, starting a stronger instability of the wake system, featuring therefore higher turbulent fluctuations. For instance, phase-averaged turbulence within the core of the tip vortices was found to experience a 100% increase, compared to the open-water configuration. Such increase was verified even more obvious within the hub vortex (fourfold). In addition, at the largest incidence instability and turbulent fluctuations at downstream locations are further enhanced by the interaction of the propeller wake with the structures originating from the tails of the upstream rudder, whose size grows with the angle of attack of the hydrofoil.

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