

NUMERICAL EXPERIMENTS FOR FLOW AROUND A DUCTED TIP HYDROFOIL

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EXTENDED ABSTRACT

Introduction. The performance and cavitation characteristics of marine propellers and hydrofoils are strongly affected by tip vortex behavior. A number of previous computational studies have been done on tip vortices, both in aerodynamic and marine applications. The focus, however, has primarily been on validating methods for prediction and advancing the understanding of tip-vortex formation in general, rather than showing effects of tip modifications on tip vortices. Studies of the most relevance to the current work include computational studies by Dacles-Mariani et al. (1995) and Hsiao and Pauley (1998, 1999). Dacles-Mariani et al. carried out interactively a computational and experimental study of the wingtip vortex in the near field using a full Navier-Stokes simulation, accompanied with the Baldwin-Barth turbulence model. Although they showed improvement over numerical results obtained by previous researchers, the tip vortex strength was underpredicted. Hsiao and Pauley (1998) studied the steady-state tip vortex flow over a finite-span hydrofoil, also using the Baldwin-Barth turbulence model. They were able to achieve good agreement in pressure distribution and oil flow pattern with experimental data and accurately predict vertical and axial velocities of the tip vortex core within the near-field region. Far downstream, however, the computed flow field was overly diffused within the tip vortex core. Hsiao and Pauley (1999) also carried out a computational study of the tip vortex flow generated by a marine propeller. The general characteristics of the flow were well predicted but the vortex core was again overly diffused.

In this study, a computational comparison of the performance of rounded tip and ducted tip hydrofoils has been performed, with the long-term goal of improving marine propeller performance by optimizing duct geometry. A ducted tip hydrofoil/propeller is one in which flow-through ducts, aligned approximately with the hydrofoil/blade chord, are affixed at the hydrofoil/blade tips. The ducted tip geometry for a hydrofoil was first proposed by Green et. al (1988). Water and wind tunnel tests have shown that the flow-through ducts suppress the tip vortex roll-up, thus resulting in a substantial delay in the onset of tip vortex cavitation (Green and Duan, 1995). This comes with little change in the lift to drag ratio. The ducted tip has also been studied on a propeller. Sea trials on a ducted tip propeller, and a conventional one of the same diameter, conducted by Hordnes and Green, (1998) showed that the cavitation inception index could be reduced by approximately 50% by installing the ducted tips. This came without efficiency loss. The efficiency of the ducted tip propeller is in fact up to 6% higher than the efficiency of the conventional propeller. In the present

study, steady flow over rounded and ducted tip hydrofoils has been studied computationally. The aim of the study was to expand our knowledge and understanding of the flow around a duct attached to the tip of a hydrofoil and thus provide a good basis for computational optimization of a ducted tip propeller blade.

Numerical implementation. The current study considers a uniform flow past two hydrofoils with a modified 64-309 cross section. One of the hydrofoils has a rounded tip whereas the other one has a duct attached to its tip. The hydrofoils, their computational domains, and the flow properties of the surrounding fluid were chosen with comparison to the experimental data of Green (1988) in mind. Both hydrofoils are without twist and taper and have an aspect ratio of 1.17. The aspect ratio is based on the semi-span. The semi-span of the rounded tip hydrofoil is measured from the root of the hydrofoil to the spanwise station where the rounding of the tip starts.

The semi-span of the ducted tip hydrofoil is based on the average spanwise distance between the root of the foil and the intersection curve between the duct and the hydrofoil. The duct has an outside diameter of $0.19c$ and is $0.67c$ long and is attached flush with the hydrofoil trailing edge, with its central axis aligned with the camber line. The thickness of the wall is $0.013c$ at the front top and bottom of the duct, but tapers off to almost no thickness along the whole outboard side of the duct as well as towards the trailing edge of the duct. The shape of the duct and its attachment to the foil have been made to resemble as closely as possible the original ducted tip hydro foil for which the experimental results are available. It is however impossible to replicate the original hydrofoil perfectly; the greatest difference between the two occurs in the area where the duct and the hydrofoil meet. On the original hydrofoil a fillet was added to smooth the intersection but that fillet has not been replicated in the computational model due to the difficulty in creating and meshing a hydrofoil with such a fillet.

The dimensions of the computational domain were chosen so that the cross section perpendicular to the freestream flow would be the same as the corresponding cross section of the tunnel in which the experiments were performed. The flow domain is 2 chord lengths high and wide. The domain extends 2 chord lengths downstream of the trailing edge and 1.25 chord lengths upstream of the leading edge of the hydrofoil. The hydrofoils are

tilted around the quarter chord line when run at an angle.

Several grid generation methods have been explored in attempts to resolve the flow near the tip vortex core and the hydrofoil surface. The multi-block grids that were used for this study consist of structured hexahedral, semi-structured prismatic, and unstructured tetrahedral blocks. The grids were generated with CFD-GEOM from CFD Research Corporation, and their basic structure will be described below. Solutions were computed by using the pressure-based, finite-volume flow solver CFD-ACE(U) from CFDRC. The code uses unstructured/hybrid grids to integrate the Navier-Stokes equations. Cases were run with a $k - \epsilon$ turbulence model and a second-order accurate upwind differencing scheme. The freestream velocity was specified for the inlet and constant pressure was specified for the outlet. A no-slip flow condition was used for the solid hydrofoil surface. Boundaries corresponding to the walls of the tunnel were specified as slip walls.

Results. The ducted and rounded tip hydrofoils were studied at angles of attack $\alpha = 7^\circ$ and $\alpha = 12^\circ$ and a Reynolds number $Re = 1.2 \cdot 10^6$. Mesh density and cell count were guided by a grid convergence study for the rounded-tip hydrofoil. The final grid used for the rounded-tip hydrofoil has approximately 536,000 cells, with wall spacing of about 0.0006-0.001 chords, corresponding to $y^+ \approx 20$; grids for the ducted-tip hydrofoil have about 20% more cells.

The primary comparison that is done here is one of surface velocity vectors obtained from the computations, and surface flow visualization (SFV) photographs from experiments done by Green (1988). Agreement between computed and experimental surface flow direction is excellent overall. The most significant differences in flow patterns for the rounded-tip hydrofoil at $\alpha = 7^\circ$ occur at the tip of the hydrofoil, where the location of the tip vortex rollup influences the flow significantly. Poor boundary layer resolution in the computation is likely responsible for part of the differences here. The discrepancy between the computational and experimental flow angles around the tip can be partly attributed to a poorly resolved boundary layer. Agreement is better for the $\alpha = 12^\circ$ case, because the tip vortex is larger and hence better resolved. The agreement between computations and experiments for the ducted tip hydrofoil is also quite good overall. The agreement between the SFV photographs and the surface vector pictures is excellent on the pressure side and very good on the duct of the hydrofoil as well. The agreement was also very good for the 7° case. For the ducted cases, some discrepancies in flow patterns relative to the experiment are present near the duct, because the computational model lacks a fillet.

Apart from validating the computational results with experimental data through surface flow visualization on the ducted and rounded tip hydrofoils, the axial and tangential velocities of the trailing vortex were studied. Computations were performed on the rounded tip hydrofoil at $\alpha = 10^\circ$ and $Re = 5.2 \cdot 10^6$ with comparison to the experimental data of Green (1988) in mind. The computed axial velocity U in the vortex core immediately downstream of the hydrofoil was 1.47, which compares well to a mean axial velocity of $U = 1.53 \pm 0.17$, measured in the center of a vortex core of a rounded tip hydrofoil of similar shape (NACA 66-209 cross section) and same aspect ratio at the same operating conditions. The corresponding maximum tangential velocities were $U_{comp} = 0.83$ and $U_{exp} = 0.80$.

Discussion. Comparing the surface flow over the rounded and ducted tip hydrofoils is a good way to assess qualitatively the performance of the different geometries. In the computations, as in the earlier experiments,

the spanwise velocity component at the trailing edge pressure and suction side, despite the fillet problem, is substantially less than that of the rounded tip. The difference in spanwise velocity component suggests that the ducted tip hydrofoil sheds less circulation over the hydrofoil surface than does the rounded tip hydrofoil. Vorticity results corroborate this. The streamwise vorticity behind the rounded tip hydrofoil is concentrated in a circle with the highest vorticity in the center of the circle whereas the vorticity from the ducted tip hydrofoil is shed in a ring with the same shape as the duct, with the highest vorticity located on the outboard side of the duct. This difference in vorticity shedding implies that the lift along the hydrofoil surface of the ducted tip hydrofoil should be higher than the lift on the rounded tip hydrofoil; sectional lift coefficients bear this out. Because the vorticity shed from the duct forms a circle with a much larger diameter than the rounded tip vortex, it is expected that the minimum pressure in the trailing vortex of the ducted tip hydrofoil is significantly higher than that of the rounded tip hydrofoil. This is in fact the case. The minimum computed pressure coefficients in the $y-z$ plane at $x/c = 1.05$ and $\alpha = 12^\circ$ are $C_{p,duct} = -1.07$ and $C_{p,round} = -2.94$. The significantly lower magnitude of the ducted tip pressure coefficient occurs in spite of a slightly higher lift coefficient for that hydrofoil. This implies that the ducted tip is likely to inhibit tip vortex cavitation inception, a finding that is in agreement with observations by Green and Duan (1995).

Future work will include continued use of CFD to optimize the duct size, shape and location on a propeller blade. This will be followed by experiments in a cavitation tunnel on a model propeller with ducted tips.

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