A sensitivity analysis of CFD transition modelling in the context of vortex roll-up prediction

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ABSTRACT

Motivated by increased awareness of the harmful environmental effects of underwater noise generated by ships, there is a need to better understand noise-generation mechanisms. An important contributor to ship noise is propeller cavitation [1]. While the numerical prediction of developed sheet cavitation is relatively well-understood, knowledge regarding modelling aspects of the inception and dynamics of tip vortex cavitation is still insufficient to obtain reliable numerical results in relation to noise predictions.

A popular approach to research cavitating vortices is by studying a tip-loaded finite span lifting surface which induces a tip vortex while avoiding rotational motion. An often-used benchmark is the elliptical $\text{NACA}66_2-415$ planform as introduced by Arndt [2]. Recent experimental [3] and numerical studies [4, 5, 6] revealed the complexity of the cavitating vortex flow. In CFD simulations, transition modelling affects the boundary layer thickness over the planform. Since the boundary layer rolls up in the wake, it is evident that the wall-bounded flow consequently affects the structure of the vortex, and in particular the viscous core size [7]. According to the analytical expression for a (non)-cavitating Lamb-Oseen vortex derived by Bosschers [1], the change in boundary layer thickness should affect the minimum pressure in the vortex. While in prior research the under-predicted vortex cavity size is explained by (i) over-prediction of the eddy-viscosity in the vortex core and (ii) numerical diffusion, it could be that the assumption of a fully turbulent boundary layer also contributes.

In order to test this hypothesis, it is important to understand the transitional behaviour of the flow over the planform under different flow conditions. To this end, a 2D sensitivity analysis of the planform at half-span towards the turbulent inflow conditions is performed prior to considering the vortex itself. Two different angles of attack (α) are considered: $\alpha = 5^\circ$ and $\alpha = 9^\circ$. Calculations are performed using ReFRESCO (`www.refresco.org`) on a set of four geometrically identical grid to assess the discretisation uncertainties [8]. The SST turbulence model is complemented with the $\gamma - \tilde{R}e_{\theta_t}$ transition model to determine the effect on the integral quantities and the transition locations. Local grid refinement around the transition locations was found to improve convergence when employing a second order accurate scheme for the convective flux discretisation in the transport equations for γ and $\tilde{R}e_{\theta_t}$. Furthermore, it was observed that the skin friction drag is much more sensitive to the turbulent inflow conditions for $\alpha = 5^\circ$ than $\alpha = 9^\circ$. The lift coefficient is found to be almost constant for both cases.

Based on these findings, a set of 3D calculations for $\alpha = 5^\circ$ is carried out for a similar range of inflow conditions. These showed a decrease of the boundary layer thickness on the suction side of a factor three when employing the $\gamma - \tilde{R}e_{\theta_t}$. It is therefore expected that for this angle of attack, the vortex structure is

strongly affected by the nature of the boundary layer.

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