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Numerical and experimental analysis of cavitation inception behaviour for high-skewed low-noise propellers

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ABSTRACT

Numerical and experimental investigations of two highly skewed low-noise propellers with a slight alteration in the tip geometry are conducted in both wetted and cavitating flows. The performance of the propellers is measured in open water and inclined setups at different operating conditions and high speed video recordings are used to determine tip vortex cavitation inception behaviour. The numerical simulations are conducted by employing the Implicit Large Eddy Simulation on appropriate grid resolutions for tip vortex propagation, at least 32 cells per vortex diameter according to our previous studies. In order to investigate cavitation inception characteristics of the propellers, different inception prediction methods are employed and evaluated at different advance ratios.

It is shown that in addition to the well-captured difference in e.g. the amount of cavitation, the simulations are capable of correctly predicting the small but crucial differences in flow features and cavitation inception characteristics of the two propeller designs. Numerical predictions of the cavitation inception charts are also compared successfully with the measured data where three different types of cavitation patterns are investigated in details. Supported by the experimental videos, the interaction between the tip vortex and trailing vortices and their impact on the pressure field and the cavitation inception are analyzed. It is shown that the numerical simulation can provide further details about the vortical flow structures, and their contributions to cavitation, and is a powerful tool in advanced propeller design stages.

1. Introduction

As tip vortex cavitation is usually the first type of cavitation that appears on a propeller, it is considered as the main controlled cavitation characteristics in the design procedure of low-noise propellers, where operating profile requires very low radiated noise emissions. In this condition, correctly predicting the cavitation behaviour of the propeller, as a function of loading conditions, is crucial in balancing difficult constraints in demanding design tasks [1,2]. Although the traditional potential flow design tools, in connection with designer experience, are able to provide optimal geometries in terms of efficiency, and to some extent the erosive cavity avoidance, generally they are not very well suited for the assessment of negative aspects of cavitating tip vortices. This limitation creates the necessity of evaluating the cavitating tip vortex characteristics of designed geometries either by model scale tests or via viscous CFD [3,4].

The main parameters defining the tip vortex cavitation inception (TVCI) behaviour of a propeller are blade geometry and load distribution [5], water quality and nuclei sizes [6,7], effects of non-uniform flow field [8–10], blade surface roughness [11,12], interactions of the tip vortices and the propeller wake [13,14], and flow Reynolds number. Moreover, the co-existence of the phase change and tip vortex creates a complex flow structure in tip regions of propellers which involve very small scale dynamics both in temporal and spatial coordinates [15–18].

Experimental observations alone can show many of the phenomena occurring in the tip region but suffer from limitations in the measurements of all relevant flow features, e.g. velocity distributions and the pressure at the vortex core where cavitation inception occurs. In this regard, numerical simulations can be employed to give further insights on the tip vortex properties that experimental tests may not be able to provide [19–21].

The numerical accuracy of TVCI predictions depends on the accuracy levels of the tip vortex flow simulations, inception model, and in the case of a slightly developed cavitating tip vortex, on the mass transfer modelling [22,23]. Due to small flow structures and very high

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flow gradients, tip vortex flow simulations demand very fine spatial resolutions along with high order numerical methodologies [24,25]. The accuracy levels of inception models also vary, and mostly depend on the modelling of nuclei dynamics. From this perspective, methods to study cavitation inception can be classified into three categories: wetted flow analysis, Eulerian cavitation simulation, and Lagrangian bubble dynamics approaches. In the simplest and computationally cheapest approach, wetted flow results are used to determine the inception points through some relations or simplified correlations between inception points and the flow properties. In the second approach, cavitation simulation has to be conducted to obtain the vapour distribution in each operating condition. Consequently, the method is more costly than the wetted flow approach. The approach that includes nuclei effects, and models the bubble dynamics behaviour in order to determine the inception point, is the Lagrangian bubble dynamics approach [26,27]. This approach can provide more details on the interactions of the nuclei and tip vortex, with an extra cost of modelling the nuclei dynamics.

The main objective of the current study is to evaluate the cavitation characteristics of two highly skewed low-noise propeller designs with slight alternation in the tip geometry, [28], in different operating conditions to explore the possibility of using CFD to support advanced propeller design work. The investigated conditions cover both wetted flow and cavitating conditions in propeller open water and inclined shaft setups. The basic design of the propellers is from a research series of five-bladed highly skewed propellers which has low effective tip load and are typical for yachts and Ro-Pax vessels, where it is very important to suppress and limit propeller-induced vibration and noise. By taking advantage of high speed video recordings, the propellers are analyzed in the RRHRC cavitation tunnel, the Hydrodynamics Research Centre of Rolls-Royce AB, Kristinehamn, Sweden.

Following previous studies conducted by the authors, the generated spatial resolutions satisfy minimum requirements of tip vortex simulations using OpenFOAM numerics, where at least 32 grid points are provided across the vortex diameter giving the spatial resolution as fine as 0.05 mm [21,20]. In order to evaluate the grid dependency of the results, three coarser resolutions are considered for one of the propellers, propeller A. The computational domains are decomposed into two regions to handle the propeller rotations by considering the relative velocity in the Navier–Stokes equation in the Multiple-Reference Frame (MRF) approach for steady simulations, or by adopting rigid body motions and sliding mesh techniques for unsteady simulations.

Several methods to predict the TVCI are used and compared in this study. The analysis includes the minimum pressure criterion and the energy of the low pressure region as a post-processing tool of the wetted flow results. The minimum vapour volume criterion, which is based on the Eulerian cavitation simulations, and the simplified uncoupled bubble dynamics criterion, based on the Rayleigh–Plesset equation, are also applied as more complex inception prediction methods.

In the minimum pressure criterion, the operating condition when the lowest pressure value of a wetted flow falls below the saturation pressure is considered as the inception point. The second method, proposed by the authors, is to consider the energy of the low pressure region of the wetted flow results. The method calculates the energy difference in a region with pressure lower than the saturation pressure and its assumed equilibrium condition at the saturation pressure, and then considers this energy as a stored energy which is released during the phase change. The model provides an estimated vapor volume that can be generated by the stored energy, and through that the inception point can be determined.

The developed cavitating tip vortex is analyzed utilizing an Eulerian Transport Based model where the flow is modelled as a single fluid mixture, considering incompressible phases for both liquid and vapour. A source term model for the mass transfer between the phases is applied [29–32]. This approach has been used by the authors, and others, successfully in simulations of cavitating flows where different cavitation regimes present in the flow simultaneously [33,34].

Finally, a simplified uncoupled Lagrangian bubble transport approach has been developed, where the dynamics of a bubble is evaluated. It is assumed the bubble travels in the core of the vortex, and the bubble radius is computed based on the Rayleigh–Plesset equation using the vortex core pressure along the path. Bubbles of different radii are tested, emulating the behaviour of strong or weak water.

In what follows, the governing equations of incompressible turbulent cavitating flows are presented. Cavitation inceptions models are discussed in the context of the wetted flow, Eulerian cavitation simulations, and bubble dynamics approach. The experimental procedure of the Rolls-Royce high-skewed propellers are described along with the computational domains employed for open water and inclined conditions. Configurations of spatial mesh resolutions for each propeller are outlined. The numerical results are presented for both wetted flow and Eulerian cavitation simulations, and compared with related experimental measurements, and snapshots. The inception characteristics of each propeller are evaluated by different models, and compared with the inception measurements.

2. Experimental test procedure

The basic design of the propellers is from a research series of highly skewed propellers having a low effective tip load and are typical for yachts and cruise ships, where it is very important to suppress and limit propeller-induced vibration and noise. In this type of propellers, the main source of noise and vibration is the vortex cavitation in the tip region. The tip vortex cavitation, and therefore the generated noise and vibration, are sensitive to the blade's geometry in the tip region. In order to investigate the influence of tip shapes and loadings on the cavitation behaviour, different designs have been suggested and tested at the RRHRC cavitation tunnel, the Hydrodynamics Research Centre of Rolls-Royce AB, Kristinehamn, Sweden.

The current study focuses on two comparable designs with differences in the tip geometry, Fig. 1. Propeller A is a Rolls-Royce standard high skew propeller with a low tip load. Propeller B is identical to propeller A except in the tip region, where a modification has been done to reduce tip vortex nuisance; the sections close to the tip of propeller B are shorter. This results in an even lower tip loading in propeller B compared to propeller A. To compensate for the reduced loading, the pitch is also increased slightly for propeller B to achieve thrust identity between the propellers.

For each propeller, thrust and torque are measured at a range of different advance numbers and cavitation numbers by changing the shaft speed and tunnel pressure at constant water velocity, unless some limitations in the measuring system require a lower velocity.

Propeller thrust and torque are measured using a force balance. Shaft speed is measured using a pulse encoder. Water velocity in the measuring section of the tunnel is measured with a Prantdl tube, taking into account the blockage effect of the upstream shaft. A non-rotating

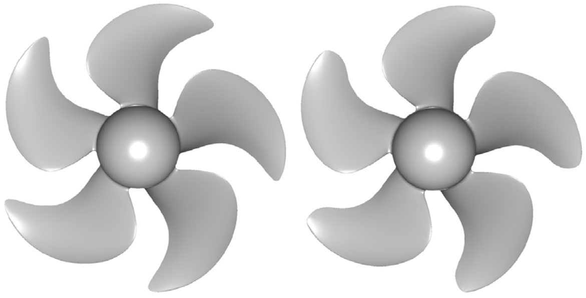
(a) Propeller A (b) Propeller B

Fig. 1. Geometries of the studied high skewed propellers.