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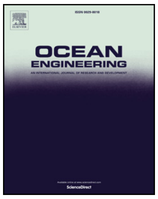

Analysis of tip vortex inception prediction methods

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ABSTRACT

The current study investigates different cavitation inception prediction methods to characterize tip vortex flows around an elliptical foil, and a high skewed low-noise propeller. Adapted inception models cover different levels of complexity including wetted flow, Eulerian cavitation simulations, and Rayleigh-Plesset bubble dynamics models. The tip vortex flows are simulated by Implicit Large Eddy Simulation on appropriate grid resolutions for tip vortex propagation, at least 32 cells per vortex diameter according to previous studies guidelines.

The results indicate that the cavitation inception predictions by the minimum pressure criterion of the wetted flow analysis are similar to weak water inception measurements. In the wetted flow analysis, the proposed energy criterion is noted to provide reasonably accurate inception predictions, similar to the predictions by Eulerian cavitation simulations with much lower computational costs.

Comparison between high speed videos and numerical results of the propeller shows the capability of the numerical methodology in predicting tip vortex structures in different conditions. The interaction between vortices and their impact on the pressure field and the cavitation inception are also highlighted. The strong dependency of the inception on the initial nuclei sizes are demonstrated, and it is shown that for weaker tip vortices this dependency becomes more significant.

1. Introduction

When a fluid passes over a finite span lifting foil, close to the tip, the pressure differential between the upper and lower surfaces of the wing drives the fluid from the high pressure side on the lower surface to the low pressure side on the upper surface. This creates a highly three dimensional rotational vortex flow (Arndt et al., 1991; Maines and Arndt, 1997; Souders and Platzer, 1981). The swirling pattern of the vortex lowers the pressure in the vortex core, and therefore, in hydrodynamic cases, cavitation can incept in the vortex core. Consequently, tip vortex characteristics of a propeller determine its inception behaviour, and therefore the boundaries of the cavitation bucket chart of the propeller (Kuiper, 1981).

Experimental measurements of tip vortex cavitation (TVC) have revealed that tip vortex cavitation inception (TVCI) is characterized by either the sudden appearance of a continuous cavity, or the intermittent appearance of an elongated bubble extending axially over a relatively small portion of the tip vortex (Higuchi et al., 1989; Arndt and Keller, 1992). The parameter determining the inception type of a tip vortex is the nuclei capture property. Cavitation occurs in the core of a tip vortex only if a nucleus has enough time to reach the core and then trigger cavitation (Boulon et al., 1997). It is well reported that this behaviour of a tip vortex depends on the nuclei radius, initial location, and the vortex circulation (Arndt and Keller, 1992; Ligneul and Latorre, 1993; Brianon-Marjollet and Inception, 1997). In some of the experimental measurements, the effects of nuclei on TVCI are addressed in the context of 'weak' water (no tensile strength) and 'strong' water (withstands pressure below the vapour pressure). Among different forms of cavitation on a blade, bubble cavitation and TVC are found to be more sensitive to the nuclei distributions (Pennings et al., 2015a; Arndt et al., 2015).

Cavitation formation, e.g. TVCI, depends on the flow Reynolds number and the blade geometry (Arndt and Keller, 1992; Fruman et al., 1995; Van Wijngaarden et al., 2005). In correlations, or scaling laws, the dependency can be represented by a dependency on the lift coefficient. Measurements of vortex singing on elliptical foils with three different cross sections (Maines and Arndt, 1997) showed vortex-boundary layer interactions are strongly coupled to the separation characteristics of each foil cross section, and lift coefficient; for an elliptical foil with NACA $66_2 - 415$ cross section, the relation is found to be $\sigma_i = 0.068 C_l^2 Re^{0.4}$. In this relation, the effects of flow unsteadiness and water quality are neglected.

The blade load distribution can also contribute to TVC (Kuiper, 2001; Baek et al., 2015). With a highly loaded tip, vorticity is generated

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in the trailing edge of a propeller blade, resulting in a trailing vortex formation. At low tip loading, separation still occurs close to the tip, while the trailing vortex is much weaker, leading to a typical local tip vortex formation. An unloaded tip forces the loading towards inner radii and at these inner radii (Dubbioso et al., 2014), leading edge separation, and therefore a leading edge vortex, may be formed. Non-uniform flow field (Pereira et al., 2016; Muscari et al., 2013; Dubbioso et al., 2013), and blade surface roughness (Dreyer, 2015; Felli and Falchi, 2011) are the other effective parameters on the type of the tip vortex of a blade.

The inception point can experimentally be determined either through visual observations of cavitation appearance, e.g. cavitation volume or tip vortex diameter (Arndt and Keller, 1992; Savio et al., 2009), or through acoustic measurements of the noise levels and then signal analysis of bubble bursting (Lee et al., 2013; Kim et al., 2015; Song et al., 2017). However, as the tip vortex involves small scales of flow dynamics, it is very difficult to experimentally measure all relevant flow features, e.g. the pressure at the vortex core where cavitation inception occurs, these methods are indirect. In this regard, numerical simulations can be employed to give further insights on tip vortex properties that experimental tests may not be able to provide (Shen et al., 2001; Schot et al., 2014; Asnaghi et al., 2017a, 2017b).

From the numerical simulation perspective, tip vortex flows are also known to be challenging flows to study because of the presence of anisotropic turbulence and the large gradients of pressure and velocity in all three directions, especially across the vortex core. The cavitation inception complicates the flow physics even further as it depends on additional flow parameters, such as the nuclei distribution, residence time, and turbulence fluctuation, which are very difficult to control during experimental tests, as well as in numerical simulations (Ligneul and Latorre, 1993; Hsiao and Chahine, 2005; Park et al., 2009; Shen and Dimotakis, 1989; Guilmineau et al., 2017). The co-existence of phase change and tip vortex creates a complex flow structure in the tip region of propellers which involves very small scale dynamics both in time and spatial coordinates. Understanding the physics of these flows is important in finding the TVCI speed in order to prevent or control the occurrence of cavitation on propellers (Bensow and Bark, 2010; Vesting et al., 2016; Zhang et al., 2014).

The numerical methods to determine the cavitation inception can generally be classified into three categories, wetted flow analysis, Eulerian cavitation simulations, and Lagrangian bubble dynamics approaches. In the simplest and computationally cheapest approach, the 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 simulations have 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 the nuclei effects, and models bubble dynamics behaviours in order to determine inception points is the Lagrangian bubble dynamics approach. This approach can bring more details on the interactions of the nuclei and tip vortex, with an extra cost of modelling the nuclei dynamics.

In the employed wetted flow approach, the minimum pressure criterion is the easiest way to determine the inception point. In this method, the operating condition when the lowest pressure value of a wetted flow falls below the saturation pressure is considered as the inception point. Considering the fact that cavitation inception is essentially a wetted flow problem, the advantage of the method is its simplicity, as it only requires the pressure field of the wetted flow simulation to determine inception points. As the method does not include the nuclei contribution on the inception prediction, it usually leads to early prediction of cavitation inception. The second method of the wetted flow approach is to employ a semi-empirical relation in order to determine inception points. A semi-empirical relation has to be derived based on experimental measurements of the inception behaviour. Each relation has to be calibrated for a specific geometry, e.g. wing or propeller, in order to correctly include the geometry effects. The relations may also have some limitations on the range of Reynolds number or water quality. The third method, proposed by the authors, is to consider the energy balance between the wetted flow results and corresponding two-phase cavitating conditions. The model assumes that in the wetted flow results the region with pressure lower than the saturation pressure has a stored energy. This stored energy is the energy that is released during the cavitation formation to provide the required energy for the mass transfer from the liquid phase to the vapour phase. The model computes this stored energy in the wetted flow simulations, and provides an estimated vapour volume that can be generated, and through that can determine the inception point.

In order to determine the inception point by Eulerian cavitation simulations, the minimum vapour volume detectable during the inception measurements has to be specified. The cavitation flow simulation condition that leads to this vapour volume is considered as the inception point.

The approach that include the nuclei effects, and model bubble dynamics behaviour in order to determine the inception point, can itself be classified into three different groups according to the level of the complexity (Kim et al., 2014). The most advanced method in this approach considers the coupling between bubbles and the flow field. The bubbles are injected upstream and then the Lagrangian equations of motion are solved for each bubble to track its path. As in this method the two-way coupling is considered, the sizes and distribution of bubbles affect the velocity and pressure field of the medium flow (Ma et al., 2017; Yakubov et al., 2013; Hsiao, Chahine). In order to include cavitation, a separate Rayleigh-Plesset (RP) equation is solved for each bubble to obtain the bubble radius at each time step. Since the relation between the bubble motion equation and the medium flow is non-linear, several inner loops have to be used between the equations to assure the convergence of the results. In order to reduce the computational costs of this method, multiscale two-phase flow Eulerian-Lagrangian approaches are developed to include tracking of micro bubbles in the micro scale along with capturing large cavities at the macro scale (Hsiao, Ma, Chahine). The impact of non-spherical bubbles can also be considered by modifying the RP equation (Choi and Chahine, 2004, 2007). However, it is reported that the shape of bubbles only becomes important during the bubble collapse time, and consequently the collapse pressure pulses, and it has a little impact on the cavitation inception prediction.

The second category, so called the uncoupled method, only includes effects of the fluid on bubbles, and assumes that effects of bubbles on the flow field are negligible. Thus the paths of the bubbles are computed based on Lagrangian equations of motions, using the background Eulerian flow field. This reduces the computational requirements as there is no need for inner loops between the bubbles equations of motion and the medium flow Navier-Stokes equations. In the third model, adopted in this study, paths of bubbles are also defined by the simulation of the wetted flow. This removes the requirement for solving bubbles equations of motion, and only the RP equation is needed to be solved by considering the surrounding pressure field to determine bubbles radii.

In this work, tip vortex simulations and analysis are conducted on an elliptical foil (Arndt, 1995, 2002) and a highly skewed low-noise propeller in order to explore the possibility of using CFD to support advanced propeller design work. The vortex structures around the elliptical foil resemble the propeller tip vortex behaviour while making it possible to be tested and evaluated in more details both experimentally and numerically. The tip vortex at the selected operating conditions is relatively stationary which reduces the computational requirements. The experiments used for validation were done by Pennings at Delft Technical University (Pennings et al., 2015a; Pennings, 2016). The selected propeller is from a research series of five-bladed highly skewed propellers which has a low effective tip load and is typical for yachts and Ro-Pax vessels, where it is very important to suppress and limit