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RANS computations of a confined cavitating tip-leakage vortex

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ABSTRACT

Cavitating tip-leakage vortices appear in several hydrodynamic flows such as marine propellers or Kaplan turbines. Cavitating computations are a challenging topic since several keys issues are an ongoing work such as the definition of a universal mass source term.

The present study focuses on the computations of the tip-leakage vortex including the gap between the blade tip and the side wall. Two computations are performed, one without cavitation and a second one with cavitation. In both cases, the results are compared with experimental data. The cavitation influence is investigated by comparing the cavitating and the non-cavitating cases. A particular attention is focused on the vortex core trajectory, the vorticity field and the vortex core identification. It is shown that, compared to the non-cavitating case, cavitation leads to a vortex trajectory closer to the suction side and the side wall, which can be of importance regarding the cavitation erosion. Furthermore, cavitation modified the vorticity field in the vortex core region. The main feature is a misalignment between the high vorticity region and the cavitating region, which opens a discussion regarding the definition of the vortex core.

1. Introduction

Tip-leakage vortices (TLV) appears in several industrial application such as airfoils, compressor engines, marine propellers and Kaplan turbines. The present study focuses on the confined TLV, which means that the gap between the blade tip and the side wall is taken into account. This flow configuration is observed for instance in Kaplan turbines. The TLV develops from the leading edge of a blade on the suction side due to the pressure difference between the pressure side and the suction side. The TLV is known to promote cavitation, which leads to several drawbacks such as erosion, flow instabilities or noise [1].

The confined TLV has been experimentally studied in the case of air compressors [2–7]. Numerical computations of these experiments have been performed using Reynolds-Averaged Navier Stokes (RANS) [8,9] or Large Eddy Simulation (LES) [10,11] modelling. The results show that the tip-leakage flow contains more than one vortex. Indeed, in addition to the TLV, one or more tip-separation vortices have been identified. The tip-separation vortices form at the pressure side of the blade and then move to the suction side through the gap. Furthermore, an induced tip vortex with a counter-rotation compared to the TLV is sometimes observed. You [10] proposed the use of the criterion proposed by Joseph [12] to determine the region where cavitation can occur. Nevertheless, no cavitation computations have been performed. Regarding hydraulic flows, Roussopoulos [13] performed cavitation investigations in relation to the development of the TLV in Kaplan-type turbine. The Particle Image Velocimetry (PIV) measurements are made on reduced simplified two-dimensional geometries. It is found that a semi-spherical casing leads to the greatest danger of cavitation erosion. Furthermore, the anti-cavitation lip tested does not prevent the risk of cavitation erosion although the circulation of the vortex is reduced.

Miorini [14] investigated the TLV in a waterjet pump rotor using PIV method. The TLV is depicted as a combination of several vortex filaments wrapping around the vortex core. The filaments never merge. The TLV displacement is depicted using the images of the vortex in both the blade and the side wall. Due to the interaction between the TLV and the side wall, a part of the boundary layer detaches and rolls up in a vortex with a counter-rotation compared to the TLV. This can be identified as the induced vortex described by You [11]. The TLV breakdowns when it approaches the pressure side of the following blade. The turbulent field shows a high value of the turbulent kinetic energy in the vortex core and in the shear layer. On the contrary, the production of turbulent kinetic energy is present only in the shear layer, which means that the turbulent kinetic energy is transported from the shear layer to the vortex core

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by means of the vortex filaments. Cavitation visualizations are used to support the TLV evolution in the blade passage.

Dreyer [15] measures the velocity field downstream a 2D NACA0009 profile for various tip gaps in absence of cavitation. These measurements reveal the influence of the gap width on the TLV behaviour. Mainly, the tip gap width is directly link to the presence of a wake or jet flow inside the vortex core. Furthermore, the authors propose a new dimensionless coefficient τ/Γ^*_∞ with τ the gap width and Γ^*_∞ the normalized circulation for the largest gap width. For $\tau/\Gamma^*_\infty \approx 0.2$, the TLV circulation reaches a peak and therefore, such a situation has to be avoided in order to reduce the risk of cavitation erosion. Flow visualizations using cavitation as a tracer put in evidence the presence of two vortices in the gap region. The TLV that forms on the suction side of the leading edge and the tip-separation vortex that forms in the gap. The tip-separation vortex moves upward and merges with the TLV. The position of the fusion between the two vortices depends on the gap with. Smaller the gap is, more upstream the fusion takes place. The presence of cavitation in each vortex depends on the gap width. Indeed, the cavitation amount in the tip-separation vortex decreases with the increase in the gap width.

Some numerical investigations of the cavitation TLV focus on the spatial inducer. Watanabe [16] carried out a two-dimensional computations based on the vortex method and a cavity growth modelled using the unsteady Bernoulli equation. Despite the simplicity of the model, the cavity growth as well as the trajectory of the vortex core is correctly captured compared to the experimental data at least for rather large gap width ($\tau > 5$). Using a similar approach, Higashi [17] is able to predict the trajectory of the vortex core for three gap widths with a good accuracy. The maximum radius of the cavity is in qualitative agreement but the position where this maximum occurs and the dynamic of the radius decrease are not well predicted. A three-dimensional inducer has been computed by Okita [18]. Turbulence is modelled using the Detached Eddy Simulation (DES) model [19] and cavitation is modelled using the model proposed by Chen [20]. It is shown that cavitation enhanced the tip-clearance flow. Moreover, the rotation of the backflow cavitation rotates with a speed lower than the rotation speed of the inducer. Nevertheless, such results are not compared with experimental data, which limits the validation of the computation. Recently, the cavitating tip leakage vortex has been investigated in an axial flow pump [21,22]. The modelling is based on a homogeneous model coupled with the SST $k-\omega$ model including the Reboud correction for the eddy viscosity [23]. The simulations show that the tip leakage vortex influences the suction side perpendicular cavitating vortex formation.

Non-confined cavitating TLV are also computed in the case of marine propellers. Hsiao [24] investigated the cavitation inception inside the tip vortex by solving the RANS equations coupled with the Baldwin–Lomax algebraic turbulence model. Cavitation is modelled using either a spherical bubble model based on the Rayleigh–Plesset equation or a non-spherical bubble model [25]. The results show that the definition of the cavitation inception and the non-spherical deformations can have an important role in order to predict the cavitation inception. A use of a surface-averaged pressure in the spherical model significantly improves the results and bring them closer to the non-spherical model. Bensow [26] performs Implicit Large Eddy Simulation (I-LES) computations of a marine propeller using the cavitation model proposed by Kunz [27]. The comparison of flow pictures with the iso-surface of the volume fraction provided by the computation shows a qualitative agreement even if cavitation in the TLV is under-resolved.

In the present paper, the TLV that develops at the tip of a NACA0009 profile mounted in a rectangular channel is investigated for one gap width. Previous non-cavitation computations for two gap widths have been carried out using RANS and LES turbulence models [28]. The comparison of the results with experimental data [15] and between the RANS and LES computations show that the RANS computations are able to capture the mean flow with accuracy. Therefore, RANS modelling is used to perform the cavitating computation. First, the computations without and with cavitation are compared with the experimental data. Then, the influence of cavitation on the TLV is discussed by comparisons with the non-cavitating case. Finally, a special focus on the cavitating TLV core is carried out.

2. Numerical tools

The computations are carried out using the OpenFOAM software release 2.1.0. This software is based on an orientated object framework [29,30].

For the non-cavitating case, the unsteady incompressible RANS equations using the Boussinesq assumptions for the turbulent stresses are solved:

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

$$\frac{\partial \vec{u}}{\partial t} + \nabla \cdot (\vec{u} \otimes \vec{u}) - \nabla \cdot \left(\nu_{eff} \nabla \vec{u}\right) = -\nabla \left(\frac{p}{\rho}\right) \tag{2}$$

with the effective viscosity $\nu_{eff} = \nu + \nu_t$. ν is the kinematic viscosity and ν_t is the turbulent viscosity. The turbulent viscosity ν_t is computed using the SST $k-\omega$ model [31]. The log wall law is assumed to compute the shear stress in the first cell layer. The time derivatives is computed with the backward second order scheme. The convective flux is discretized with the Total Variation Diminishing (TVD) scheme named "limitedLinear" specific to OpenFOAM. The limiter is defined as $\Psi(r_f) = \max(\min(2r, 1), 0)$. The time derivative is discretized using the second order backward scheme. The set of equations is solved by using a coupled SIMPLE/PISO algorithm.

For the cavitating case, the homogeneous mixture approach is used. Therefore, the two phases share the same velocity, pressure and temperature. Furthermore, in the present work, the temperature is assumed constant. The mixture density ρ and the mixture kinematic viscosity ν are computed as the phase average of the phase value:

$$\rho = \alpha_L \rho_L + (1 - \alpha_L)\, \rho_V \tag{3}$$

$$\nu = \alpha_L \nu_L + (1 - \alpha_L)\, \nu_V \tag{4}$$

with:

- $\rho_L = 1000$ kg m^{-3}, the liquid density.
- $\nu_L = 9 \cdot 10^{-7}$ m^2 s^{-1}, the liquid viscosity.
- $\rho_V = 0.02$ kg m^3, the vapour density.
- $\nu_V = 4.473 \cdot 10^{-4}$ m^2 s^{-1}, the vapour viscosity.
- α_L, the liquid volume fraction.

The set of equations to be solved is:

$$\frac{\partial \alpha_L}{\partial t} + \left(\vec{u} \cdot \nabla\right) \alpha_L = S \tag{5}$$

$$\nabla \cdot \vec{u} = \left(\frac{\rho_V - \rho_L}{\rho}\right) S \tag{6}$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u} \otimes \vec{u}) - \nabla \cdot \left(\mu_{eff} \nabla \vec{u}\right) = -\nabla p. \tag{7}$$

Eq. (5) is the transport equation for the liquid volume fraction with S the source term. It is modelled using a slightly modified version of the model proposed by Kunz [27] (effects of non-condensable gases are non-considered), which splits the source term[1] in a

[1] In the OpenFOAM formulation, the source terms are multiplied by the factor $\rho/(\rho_L \rho_V)$ compared to the formulation proposed by Kunz