Numerical simulation of the cavitation micro–jet velocity and erosion on a plane–convex hydrofoil with semicylindrical obstacle

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Abstract.

The present study deals with the numerical study of the cavitation micro–jet velocity and erosion on a plane–convex hydrofoil with semicylindrical obstacle, which induces a big cluster of cavities with a strong erosive power. The proposed model predicts micro-jet velocities based on energy conservation by assuming potential and kinetic energies at the start and the end of the cavity collapses. Homogeneous mixture flow, implicit LES and Zwart-Gerber-Belamri cavitation model have been used for the numerical simulation of the unsteady cavitating flow using OpenFOAM, whilst for the micro-jet estimation, Python language coupled with OpenFOAM’s calculator have been used. Results clearly show that the implemented model captures adequately the phenomenon and enables to identify attacked areas. Outcomes agree reasonably with the experimental results obtained by Escaler at the High Speed Cavitation Tunnel of the École Polytechnique Fédérale de Lausanne (EPFL). Furthermore, the proposed model has been compared with Li’s and Peters’ ones for a better understanding of the improvements.

Keywords: cavitation-erosion; micro-jet velocity; OpenFOAM; plane–convex hydrofoil

1. Introduction

Studies of cavitating flows are important to understand the main mechanics of the induced erosion on hydraulic machinery components, which are related to machinery stop and the increase of maintenance costs [1, 2]. Considering that, previous studies were focused on the prediction of the eroded region on hydrofoils using a post processing procedure of CFD simulations [3, 4].

Li et al. [3] proposed an erosion intensity function, $I_{erosion}$, which is a model based on the partial derivative of pressure, $p$, with respect to time $t$. However, $\partial p/\partial t$ can not only predict affected regions by cavities collapse, but also some regions affected by the turbulence of the cavitating flows. Therefore, the estimated threshold of $I_{erosion}$ could not be easily estimated without previous experimental results. Another interesting model was proposed by Peters et al. [4], and it considers the high speed jets and the water hammer produced after cavities collapse [5, 6]. In this matter, the authors of that model calculated the magnitude of the critical velocity, $u_{cri}$, to estimate the plastic deformation on a specific material. However, the idea of

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potential energy stored in cavities proposed by Bark et al. [7] and Patella et al. [8] was not considered, and it is important to understand the resulting micro-jet [9].

Bearing in mind these aspects, Hidalgo [9] proposed a cavitation-erosion model using OpenFOAM and Python language, which joined the potential energy in cavities with the kinetic energy in the micro-jet. In this context, the proposed model has been applied to study cavitation-erosion on a plane-convex hydrofoil with semicylindrical obstacle [10] and compared to the aforementioned models of Li and Peters.

2. Model description
For the numerical simulation of unsteady cavitating flows, homogeneous mixture flow assumption, implicit LES turbulence model (ILES) and the Zwart-Gerber-Belamri cavitation model (ZGB) were applied [11]. For the proposed model, the dimensionless micro-jet velocity, $c_{\text{flow}}$, is expressed in (1) as a function of the micro-jet velocity, $u_{\text{jet}}$, and the undisturbed flow velocity, $U_{\infty}$.

$$c_{\text{flow}} = \begin{cases} 8.97\gamma^2 \sqrt{\frac{(p - p_v)}{\rho l U_{\infty}^2}} \left( \frac{\alpha_o - \alpha_f}{\alpha_o} \right), & \text{if } (\alpha_o - \alpha_f) > 0 \text{ and } (p - p_v) > 0, \\ 0, & \text{if } (\alpha_o - \alpha_f) < 0 \text{ and } (p - p_v) < 0 \end{cases},$$

where $\gamma$ is a dimensionless distance from the bubble centre to the wall [5], $p$ is the static pressure, $p_v$ is the water saturation pressure, $\rho_l$ is the density of the liquid water, $\alpha$ is the vapor volume fraction, and subscripts $o$ and $f$ denote the initial and final instant of the cavity collapse, respectively.

Furthermore, a qualitative value of flow aggressiveness, $\tau_{\text{flow}}$, can be estimated using (2) to predict the affected region in relation with its maximum value after one characteristic cavitation cycle. Where $i$ is the subscript for each affected cell, and $t_o$ and $t_f$ are the initial and final time of the characteristic cavitation cycle respectively.

$$\tau_{\text{flow}} = \frac{\max \left( \sum_{t_o}^{t_f} c_{\text{flow}} \right)}{\sum_{t_o}^{t_f} c_{\text{flow}}}. \quad (2)$$

Li’s functions, $I_{\text{erosion}}$, and Peter’s deformation coefficient, $c_{\text{def.}}$, have been used to compare with the proposed $\tau_{\text{flow}}$. The mathematics of the aforementioned models of Li and Peters are indicated in references [3] and [4], respectively.

3. Computational domain and boundary conditions

![Computational domain of a plane-convex hydrofoil with semicylindrical obstacle.](image)
The computational domain and boundary conditions indicated in figure 1 were based on the experimental studies carried out by Escaler in the Laboratory of Hydraulic Machinery of the École Politéchnique Fédérale de Lausanne (LHM–EPFL) [10]. It is noted that the chord length of the hydrofoil, $c$, is equal to 91.1 mm, and $U_\infty$ is equal to 35 m/s based on [9, 10].

The purpose of the so-called semicylindrical obstacle located close to the leading edge has been to alter the flow field in order to increase the cavitation aggressiveness [10].

A structured mesh was generated using the GMSH 2.8.5, which is a free open source software [12]. That mesh was optimized using exponential distribution of cells, and the total number of hexahedral elements is equal to $3 \times 10^5$ as indicated in figure 2. Furthermore, the estimated mean of $y^+$ is close to 2, and it is computed according to previous studies [11, 13].

4. Results and discussion

For a better understanding of the unsteady cavitating flow, iso-surfaces of $Q$-criterion equal to $1 \times 10^7 \text{s}^{-2}$ and the vapor fraction, $\alpha$, equal to 0.1 were been plotted in figure 3 (a) and (b), respectively. This characteristic cavitation cycle was selected based on [9] and the $Q$-criterion was estimated by using (3).

\[
Q = \frac{1}{2} (\Omega_{ij} \Omega_{ji} - S_{ij} S_{ji}), \tag{3}
\]

where $\Omega$ is the vorticity rate, and $S$ is the strain rate. The growth of the detached cavity is indicated from instant (i) to (iii) in figure 3 and the shedding-collapse from (iv) to (v) of the
same figure. Furthermore, residual cavities are observed at instants (i) and (v), which are related to nucleation cores for vaporization structures.

Experimental and numerical results of erosion after one cavitation cycle are compared in figure 4 for $I_{\text{erosion}}$, $c_{\text{def.}}$, and the proposed $c_{\text{flow}}$. The half part of the experimental results is located at the left side and the half part of the numerical result at the right side for each case. Basic characteristics of the erosion shape were good enough obtained using $c_{\text{def.}}$ and $c_{\text{flow}}$, which are based on $u_{\text{jet}}$. $I_{\text{erosion}}$ shows an erosion prediction inside and outside of the affected region with shapes different than experimental results, that could be possible due to the fact that $\partial p/\partial t$ is also related to the turbulence of flows. Furthermore, the most affected region detected using $c_{\text{flow}}$ matches the experimental result zone better than $c_{\text{def.}}$, due to the consideration of $\alpha$ inside of the $u_{\text{jet}}$. In this context, the proposed qualitative value, $c_{\text{flow}}$, shows improvements compared to $c_{\text{def.}}$ and it is an update of previous models.

![Figure 4: The comparison of the affected region at the tunnel test of EPFL after 75 hours [10] with numerical results of $I_{\text{erosion}}$, $c_{\text{def.}}$, and $c_{\text{flow}}$.](image)

5. Conclusions

Results of the present research agree reasonably with the experimental results of cavitation-erosion on a plane-convex hydrofoil with semicylindrical obstacle. The study confirms the possibility to use the present method for cavitation erosion prediction on hydrofoils, and the proposed model is an update of previous studies with good improvements on the prediction of the affected regions and eroded shape.

Acknowledgments
The authors gratefully acknowledge the financial support provided by Escuela Politécnica Nacional (Project No. PIJ 17–13).

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