A Methodology to Identify Erosive Collapse Events in Incompressible Simulation of Cavitating flows

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1 Introduction

Cavitation erosion is one of the limiting factor in the design of hydraulic machineries such as propellers, pumps, diesel injectors, etc. The material loss due to cavitation erosion imposes restriction on the performance of hydraulic systems and leads to significant increase in maintenance and repair costs. It is therefore essential to evaluate the risk of cavitation erosion in the design process. In marine applications, the erosion risk is usually assessed by experimental investigations on model scale. Visual assessment of collapsing cavities using high speed video (Bark et al.,2004) complemented by paint test and/or acoustic measurement(van Rijsbergenet al.,2004) has been used for this purpose. As the experimental assessment of cavitation erosion are usually applied in model scale, the risk of erosion on the full scale are assessed by calibrating the assessed risk of erosion in model scale using ad hoc correlations and experience.

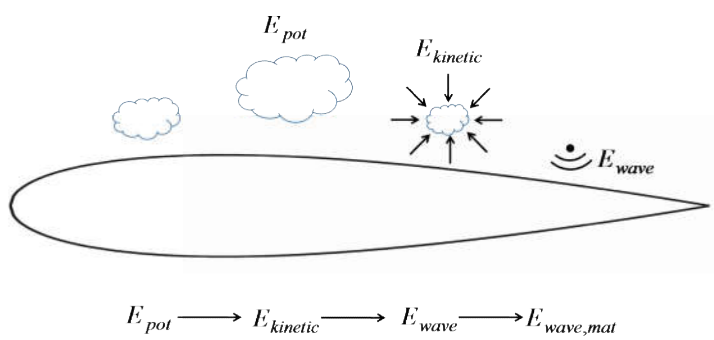


Fig. 1: A sketch of cavitation erosion mechanism based on a concept of energy cascade

Over the past decade, a significant progress has been made in numerical modelling of cavitating flows. Several numerical studies have shown that current numerical methodologies are capable of reproducing the main feature of cavitating flows,see e.g. Bensow and Bark(2010) and Asnaghi et al.(2017). It is thus becoming feasible to proceed with the development of numerical erosion indicators models that can predict the risk of erosion based on the result of numerical simulation. van Terwisga et al.(2009) reviewed several erosion models and concluded that the model for erosion mechanisms as described by Bark et al.(2004) and Fortes-Patella et al. (2004) are suitable for numerical prediction of cavitation erosion. These models are based on the concept of hydrodynamic energy cascade which considers an energy balance between the potential energy of collapsing vapour structures and surface material damage, although from two slightly different perspectives. Based on this energy balance, Bark et al.(2004) introduced the concept of kinematic focusing of collapse energy which describes that the energy of collapsing cavities is focused into small area of the surface material in an erosive collapse(Fig. 1). According to Bark et al.(2004), when a cavity expands in the low pressure region, the surrounding liquid gains potential energy. This potential energy is transformed into kinetic energy when the cavity collapses in the pressure recovery region. At the end of the collapse, the kinetic energy of the liquid is converted into acoustic energy which is radiated through pressure waves in the surrounding liquid, alternatively acts as a water hammer or micro jet against the material. Fortes-Patella et al.(2004) provided a similar description for erosive eventsand described that some part of the acoustic energy is absorbed by the material when the emitted pressure waves hits the surface. If the absorbed energy exceeds a certain threshold which is a function of material properties, cavitation erosion can occur.

The aim of this study is to present a numerical tool that can identify the erosiveness of a macro-scale collapsing cavity, based on the concept of hydrodynamic energy cascade introduced in the EroCav Handbook(Bark et al., 2004). The proposed numerical method is applied for the cavitating flow over a 3D NACA0015 foil. Erosive collapse events are identified and their locations are compared with experimental erosion pattern by Rijsbergen et al. (2012).

2Methodology

The potential energy of a cavity at the start of the collapse is defined as

$$E_{pot} = V_0 \triangle p \tag{1}$$

where $\triangle p = P_\infty - P_v$, $P_v$is the vapor pressure, $P_\infty$is the liquid pressure at infinity, and $V_0$is the initial volume of the cavity. Based on the concept of energy cascade, Fortes-Patella et al(2004) proposed that the aggressiveness of a collapsing cavity can be assessed by a parameter called the collapse efficiency, η. This parameter determines what percentage of the potential energy of a cavity,E_{pot}, is transformed into acoustic energyE_{wave} and is defined as

$$\eta = \frac{E_{wave}}{E_{pot}}. \tag{2}$$

Fortes-Patella et al. (2013) found that the collapse efficiency is a strong function of liquid pressure at infinity,P_∞, and initial gas pressure inside the bubbles, P_{g0}, and can be expressed as

$$\eta = 0.029(\frac{P_\infty}{P_{g0}})^{0.54}. \tag{3}$$

If hydrodynamic conditions (P_∞ , V_0, P_{g0}) of a collapsing cavity are known, equations(1)-(3)can be used to estimate aggressiveness of collapse events. However, it is difficult to derive the liquid pressure at the infinity, P_∞ and the initial volumeV_0 for a collapsing cavity in the simulation results. An alternative approach could be to estimate these two parameters according to the kinematics of collapsing cavities. This approach is based on the EroCav handbook(Bark et al., 2004)which has hypothesized that the kinematic feature of a collapsing cavity controls the aggressiveness of the collapse. Here maximum collapse rate, $\dot{V}_{max}$, and the volume of the bubble at maximum collapse rate, $V_{\dot{V}max}$, are considered as the collapse kinematic features of interest. In order to apply the EroCav handbook approach, equations should be derived to relate potential Energy E_{pot}, collapse efficiencyη and the kinematic feature of the collapse($\dot{V}_{max}$,$V_{\dot{V}max}$). In this study, these equations are derived from a parametric study on the collapse of spherical bubbles using the Rayleigh-Plesset equation(Rayleigh,1917). If we substitute these equations into equations (2) and (3), the final equation for E_{wave} as a function of kinematic feature of collapse($V_{\dot{V}max}$, $\dot{V}_{max}$), liquid densityρ_l, and initial gas pressure inside bubblesP_{g0}, can be derived as

$$E_{wave} = 2.06 \times 10^{-3} P_{g0}^{-0.54} \rho_l^{1.27} V_{\dot{V}max}{}^{-1.053} \dot{V}_{max}{}^{3.08}. \tag{4}$$

We further assume that the acoustic energy E_{wave}propagates from the collapse centre by a spherical wave. When this spherical wave hits the surface, some part of the acoustic energy is absorbed by the material. The amount of acoustic energy absorbed by the surface element with area ΔS can be calculated from

$$E_{wave,mat} = e_{wave}(r)\Delta S = \frac{E_{wave}}{4\pi d^2} \Delta S, \tag{5}$$

where d is the distance between surface element and the collapse centre. In this study, the maximum value of $E_{wave,mat}$ for each surface element are used to predict areas with high risk of cavitation erosion.

In order to obtain the maximum collapse rate of a collapsing cavity, it is required to evaluate the collapse rate of each cavity before the final collapse. This task is done by a numerical tool that can track each cavity and save its maximum collapse rate. The methodology used in this numerical tool is similar to the one presented in Silver and Wang (1998). At each time step, cavities are extracted from the list of cells with vapor fraction larger than a threshold and negative vapor mass transfer. These cavities are tracked between consecutive time steps by finding the best match for the cavities in time *t+1* from the list of cavities in time step *t*. The criterion for finding the best match is based on overlap checking. Cavities in time step t that cannot be matched with cavities in time step *t+1* are considered as collapsed cavities. The kinematic feature of these cavities and their collapse points are written into a file as an output of the tracking tool. A post-processing tool reads this file and calculates the $E_{wave}$for each collapsed cavity and the maximum value of $E_{wave,mat}$ for each surface element based on equations(4)and (5).

3 Results

The above described erosion indicator is applied to estimate the erosion pattern in a cavitating flow over a NACA0015 foil. The flow configuration is the same as the one used in the experimental study by Rijsbergen et al. (2012). A summary of flow condition is presented in Table 1. For this flow condition, the experimental study has shown that the cavitating flow has a periodic shedding of cloud cavitation due to a re-entrant jet mechanism; shedding frequency of 188Hz was observed in the

Table 1Flow condition

Cavitation Number	2.01
Reynolds Number	9.5×10^5
Inlet Velocity	17.3 m/s
Chord Length	0.06 m
Angle of Attack	8^o

experiment. For this simulation, the incompressible interPhaseChangeFoam solver from the OpenFOAM framework is used for the simulation. A mixture modelling approach is used to consider cavitation combined with an explicit transport model where mass transfer is modelled using the Schnerr-Sauer model. Turbulence is considered using an implicit LES approach where the numerical dissipation acts as the sub-grid scale model.

The computational domain is a 3D channel with height of 0.08m and width of 0.02m. To decrease the computational cost, the computational domain includes only the half span of the 3D NACA0015 foil and asymmetry condition is applied to the middle plane. The channel is extended 3 chord lengths upstream of the foil leading edge and 5 chord lengths behind of the trailing edge. Fig.2 shows the mesh topology used in this simulation. The domain is divided into two regions where the region near the foil is discretised with a structure hexahedral O-type mesh and the outer region is discretised with an unstructured mesh. The average value of y+ around the foil is less than 1 and the maximum value of x+ on the upper surface of the foil is around 150. In the span-wise direction, the z+ is less than one close to the channel side wall and around 300 near the symmetry plane.

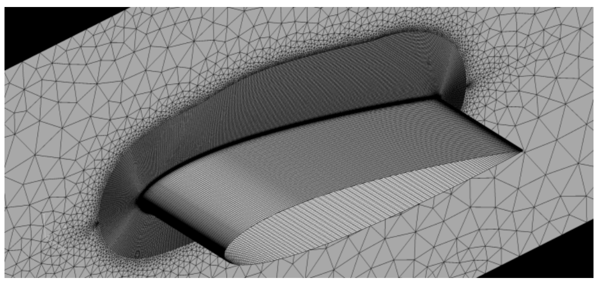
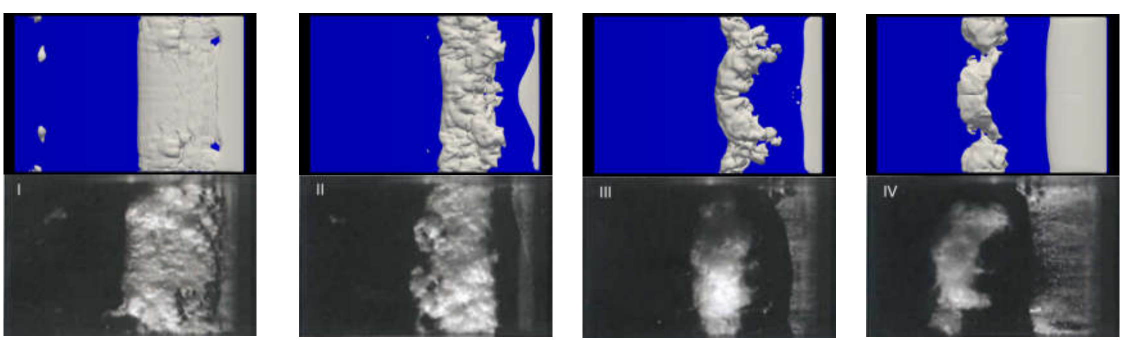


Fig.2Mesh topology used for the simulation of cavitating flows over NACA0015 foil

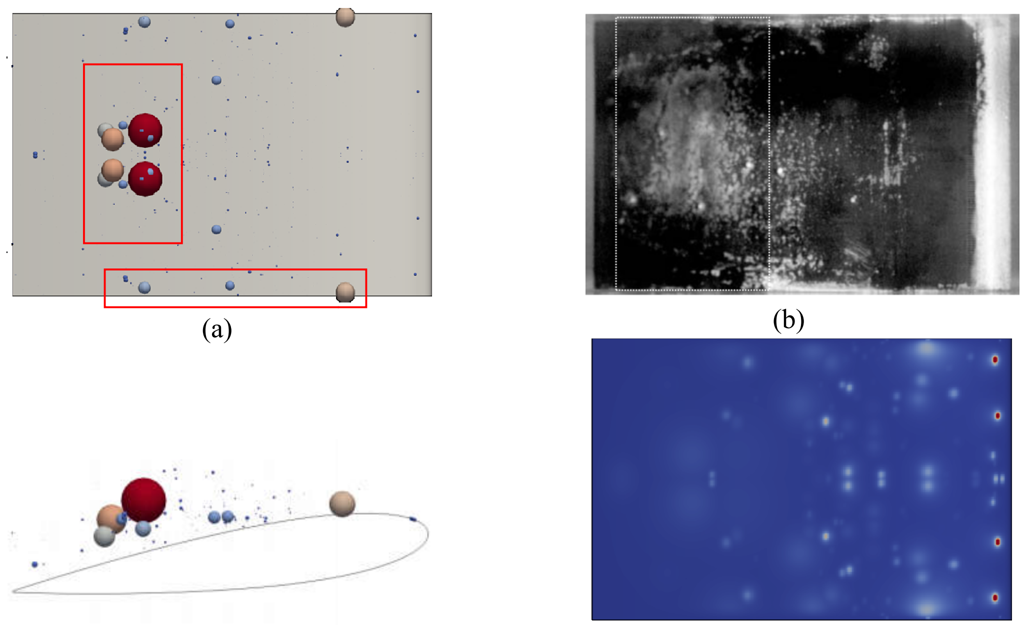
Fig.3 shows the comparison between the breakup of the sheet cavity and the shedding of cloud cavitation in the numerical simulation and the experimental observation. Numerical results compare well with the experimental observations. In Fig.3-a, the re-entrant jet moves upstream and cuts the interface of the sheet cavity close to the leading edge. As a result, a cloudy cavity structure is formed with circular motion due to interaction between the re-entrant jet flow and bulk flow(Fig.3-b). This circular motion gives the cloud cavity a cylindrical shape(Fig.3-c). As the cloud goes downstream, it



a) $t = t_1$ b)$t = t_1 + {}^{3}/_{20}T$ c)$t = t_1 + {}^{6}/_{20}T$ d)$t = t_1 + {}^{9}/_{20}T$

Fig.3: Cloud shedding in one cycle: Top) Numerical simulation results; Bottom) experimental observation taken from Li(2012)

breaks up into two structures(Fig.3-d). Structure 1, which is located in the centre, is transformed into horse-shoe shape and the legs of this horse-shoe shape is attracted toward the surface due to vortex stretching. Structure 2 in Fig.3-d travels downstream and remains close to the side walls. Fig.4shows the comparison between the erosion assessment using of the developed methodology as described in this study with the experimental results of van Rijsbergen et al. (2012). The erosion obtained by the soft paint shows that areas with high risk of erosion are located mainly in the downstream half of the foil where the cloud cavity collapses, and in the regions close to the tunnel walls. The location of collapse points and their emitted acoustic energy are shown in Fig.4-a where each sphere is a collapse point and its size and colour represents its emitted acoustic energy, E_{wave}, estimated by equation(4). The collapse points with high emitted acoustic energy are from the collapse of horse-shoe structure and the structures close to side walls (Fig.3). The locations of these collapse points agree well with the erosion pattern from the paint test. Fig.4-d shows the maximum value of acoustic energy absorbed by each surface element of the foil, $E_{wave,mat}$, as computed using equation(**5**). The maximum value of $E_{wave,mat}$ on the foil surface is located on the leading edge where the collapse of the sheet cavity occurs. As no paint was applied in the area close to the leading edge in the experimental paint test, the predicted erosion on the leading edge absorbed acoustic energy on foil cannot be compared with the experiment. Although there are some collapse points with high emitted acoustic energy in the areas close to the trailing edge in Fig.4-a and Fig.4-c,Fig.4-d shows that the calculated maximum $E_{wave,mat}$issmall in these areas. The reason might be that the collapse point in these areas are far away from the surface, therefore $E_{wave,mat}$due to these collapses are underestimated by equation(**5**). The erosiveness could also be influenced by some other focusing mechanisms not considered in this implementation.



(a) (b) (c) (d)

Fig.4: a) and c) The location of collapse points and their emitted acoustic energy, b) experimentalerosion pattern obtained by soft paint, d) the erosion pattern predicted by the maximum value of absorbed acoustic energy on foil.

4 Conclusions

In this study, a new methodology is presented that can identify areas with high risk of cavitation erosion in an incompressible simulation of cavitating flows. The methodology is based on the concept of hydrodynamic energy cascade which considers an energy balance between the energy of collapsing cavities and erosion damage. Using this concept, the emitted acoustic energy of each collapse event is estimated as function of kinematic features of the collapse. The proposed numerical method is applied for the cavitating flow over a 3D NACA0015 foil. The collapse points with high emitted acoustic energy are indentified and their locations are compared with experimental erosion pattern by Rijsbergen et al. (2012). The comparison shows that the location of these collapse points agrees well with the erosion pattern from the paint test. However, the erosion pattern predicted by the maximum value of absorbed acoustic energy on the foil shows discrepancies when compared with the experimental erosion pattern. The reason for this discrepancy might be that collapse event with high emitted acoustic energy are predicted to occur at wrong distance to the surface, therefore their erosiveness is underestimated. Other reasons might be a too simplistic relation for the attenuation of the emitted pressure wave.

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