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Prediction of cavitation erosion for marine applications

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Prediction of cavitation erosion for marine applications

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Abstract. The paper presents the development of a cavitation erosion prediction method. The approach is tailored to marine applications and embedded into a VoF-based procedure for the simulation of turbulent flows. Supplementary to the frequently employed Euler-Euler models, Euler-Lagrange approaches are employed to simulate cavitation. The study aims to convey the merits of an Euler-Lagrange approach for erosion simulations. Accordingly, the erosion model is able to separate different damage mechanisms, e.g. micro-jets, single and collective bubble collapse, and also quantifies their contribution to the total damage. Emphasis is devoted to the prediction of the cavitation extend, the influence of compressible effects and the performance of the material damage model in practical applications. Examples included refer to 2D validation test cases and reveal a fair predictive accuracy.

1. Introduction

Cavitation erosion is frequently observed in marine and hydraulic engineering, e.g. ship propellers and rudders, pumps or turbines. Due to the severe risks associated to operations under sustained erosive cavitation, the accurate prediction of cavitation erosion is of great importance from an industrial point of view. Such modelling approaches would allow replacing model tests by numerical simulations during the preliminary design phase and thereby yield a reduction of the expenditures and time frame. However, cavitation erosion predictions based on numerical models are a challenging problem for the computational fluid dynamics and computational engineering community. The challenges particularly refer to the wide range of involved scales of the compressible multiphase flow, but also the response of the solid materials and the influence of individual bubbles or the initial nuclei population.

When attention is given to the simulation of erosive cavitation, the erosion mechanisms are often masked by considerable modelling efforts inherent to the usually employed Euler-Euler modelling framework. Erosion is associated with strong pressure changes and travelling pressure waves, whose amplitude depends on the bubble sizes. It is thus almost inaccessible for Eulerian approaches which do not resolve down to the bubble scale. The present research aims to assess the predictive improvements offered by an Euler-Lagrange approach, which employs a dispersed Lagrangian vapour phase model and thereby provides access to vapour bubbles physics and realistic pressure-wave predictions.

2. Numerical Model

Results of the present study are obtained from the in-house solver FreSCo^{+} [1]. The finite volume procedure uses a segregated algorithm based on the strong conservation form of the governing equations and employs a cell-centered, co-located storage arrangement for all transport properties. The solution is iterated to convergence using a modified SIMPLE method for pressure-velocity coupling [2]. The schemes takes into account for density variations due to cavitation using an additional source term in the compressible pressure-correction equation. A linearisation of this source term ensures a stable convergence for both steady and transient cases. Multiphase problems are addressed by an Euler-Euler VoF approach or an Euler-Lagrange technique.

The most popular technique to simulate cavitating flows refers to the VoF-based Euler-Euler approach [3]. It considers the two-phase flow as mixture of a liquid and a vapour phase which share the kinematic field. The vapour-volume fraction is computed from an additional transport equation that heuristically models the mass transfer between vapour and liquid using various empirical constants. The model parameters are unfortunately not universal and interact with the employed computational algorithm [4]. On contrary, the two-way coupled Euler-Lagrange approach allows to compute the evolution and motion of individual vapour bubbles [5]. Supplementary to an Eulerian mixture phase, separate equations for the size and the momentum are solved for each individual cavitation bubble/nuclei. The field properties follow from the Eulerian conservation equations, whereas the vapour part is governed by Newtonian motion of individual bubbles driven by the surrounding flow field. The present study employs a parallelised two-way-coupled strategy and accounts for inhomogeneous and transient water-quality effects such as nuclei spectra [6]. The resolution of yield loads (e.g. copper: 200 MPa) and the prediction experimentally observed pressure peaks in the range 0.8 to 2 GPa are crucial for a direct assessment of cavitation erosion, but pose a severe challenge for the computational model. Regarding Euler-simulations, reported values are limited to approximately 100 MPa, while for our Lagrange simulations realistic pressure peaks up to 1 GPa are seen. This yields the conclusion that for a quantitative prediction, Lagrange models offer benefits over Euler models.

3. Erosion assessment

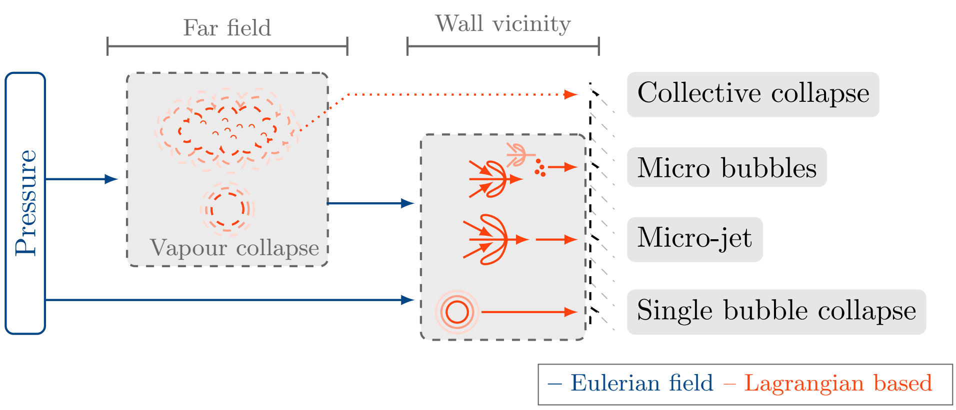

Figure 1. Erosion damage mechanism cascade using an Euler-Lagrange approach.

The study compares results obtained from Eulerian and Lagrangian modelling frameworks. Within the Eulerian approach an enhanced micro-jet model for erosion prediction is used [7]. The idealized mechanism focusses on (unresolved) small bubbles in the vicinity of the surface, that produce a micro-jet during their pressure induced collapse. The parametrised micro-jet is deemed responsible for the pitting of the solid surface. The model requires an assumption of the size and the population of small bubbles close to the wall - including their wall distance - and a threshold for an activation pressure. The corresponding mathematically framework can be coupled to the Euler-Euler cavitation approach without problem. However as it does not resolve any of the responsible mechanisms, it inheres a considerable amount of empiricism. An example refers to the ambiguity of the bubble state for a given mixture state, i.e. it is not clear what bubble spectrum composes a mixture.

Cavitation erosion has its origin in the collapse of cavitation structure whereby depending on the cavitation type the erosion aggressiveness varies. Hence a numerical prediction method needs to diversify cavitation type and rely on miscellaneous erosion definitions. The Lagrangian approach provides information about the cavitation type by evaluating the bubbles size and position and therewith overcoming the difficulties of the Eulerian mixture phase. Additionally these parameters allow to distinguish between the state of the art defined erosion mechanism. The overall Euler-Lagrange damage mechanism cascade is illustrated in Figure 1. Due to the Lagrangian treatment of the vapour phase (bubble parameters and position to the solid surface), the method covers the following range damage mechanisms:

(1) Symmetrical bubble collapse in the vicinity of the wall [8]

(2a) Micro-jet from asymmetrical collapse of bubbles very close to wall [9]

(2b) Erosion damage from micro bubbles created after asymmetrical bubble collapse [10]

(3) Collective collapse of multiple bubbles in cascade [11]

The erosion damage is calculated in Lagrangian manner. The compressible Rayleigh-Plesset equation accounting bubble interaction are solved for each bubble and the micro-jet model is used for bubbles in the vicinity of the wall. The choice of erosive mechanism is coupled to the wall distance of the respective bubble and the occurrence of neighbouring bubbles. The pressures are evaluated in the Lagrangian model. The commonly smaller Lagrangian time step compared to the one from the Eulerian background fluid field supports the resolution of pressure waves and enables an exact derivation of the erosion damage. On the other hand, Eulerian physics is retained and can be an important aspect, e.g. when considering the pressure waves of collapsing vapour structures away from the wall.

4. Validation

Table 1. Variation of the erosion rate with the ref. velocity for flow through a venturi nozzle.

Case	Spec. material	Ref. vel. [m/s]	Cav. number	Exponent
Exp. He and Hammitt [12]	aluminium/steel	30-50	0.76	4.0/1.1
Exp. Knapp [12]	soft aluminium	20-30	ci. 0.3	6.4
			0.85	9.2
Sim. FreSCo$^+$	aluminium	30 -50	0.76	6.4
			0.62	3.2

The first example is a simple two-dimensional venturi nozzle experimentally analysed by He and Hammitt [12]. Emphasis is given to the prediction of scale effects, i.e. the behaviour of the erosion rate R in response to an increase of the reference velocity V at constant cavitation number. Results are compared in terms of a corresponding exponent n, $R \sim V^n$. Table 1 summarises the experimentally reported and numerically obtained exponents.

The erosion of a circular leading edge hydrofoil has often been experimentally analysed, e.g. [7]. Figure 2 shows the erosion damage after 1 h of exposure. On the right a photography of the experimental damage illustrates the top view on the airfoil surface. The diagram on the left side compares the experimental and simulated (modified Euler-Euler approach) span-averaged surface damage. The numerically predicted damage is in reasonable agreement with experiments. Only around $x \sim 40\,\mathrm{mm}$ (i.e. $x/C = 0.37$) a major discrepancy is observed. Here, the cavitation clouds separate from the foil and the deficits of Euler-Euler approach, i.e. the activation pressure assignment to the wall, whip hand.

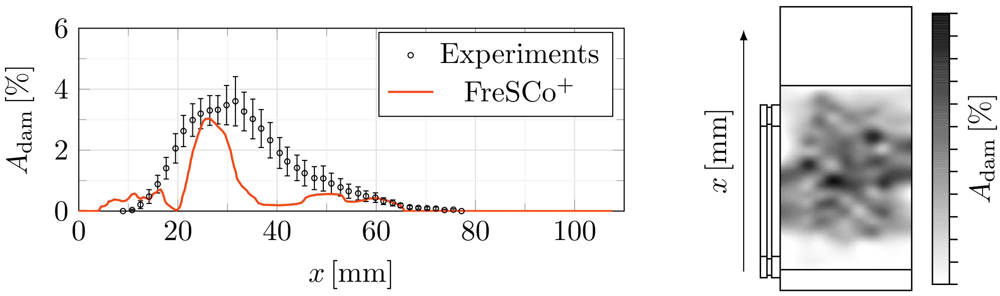

Figure 2. Erosion damage after 1 h exposure on the CLE hydrofoil (Exp. [7]).

5. Conclusions

In this study two approaches for assessing cavitation erosion are described. The well known Euler-Euler approach to simulated cavitating flows combined with an enhanced micro-jet erosion models shows satisfactorily results when appropriately adjusted to benchmark cases. However the empiricism of the technique remains the major deficit. The second approach employs using the Euler-Lagrange method and answers most of the weak spots per definition. The exact location, size and history of the bubbles are known and are used instead of empirical assumptions. Additionally cascade collapse and micro bubbles can be computed to account for further erosion mechanisms. However the computational cost increases with each feature and needs to be addressed. More results related to the above depicted Euler-Lagrange approach within the FreSCo$^+$ framework will be presented at the conference.

Acknowledgments

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