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A cavitation aggressiveness index within the Reynolds averaged Navier Stokes methodology for cavitating flows*

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Abstract: The paper proposes a methodology within the Reynolds averaged Navier Stokes (RANS) solvers for cavitating flows capable of predicting the flow regions of bubble collapse and the potential aggressiveness to material damage. An aggressiveness index is introduced, called cavitation aggressiveness index (CAI) based on the total derivative of pressure which identifies surface areas exposed to bubble collapses, the index is tested in two known cases documented in the open literature and seems to identify regions of potential cavitation damage.

Key words: cavitation aggressiveness index (CAI), cavitation erosion, multiphase cavitating flows

Introduction

Cavitation is a phenomenon commonly associated with the appearance of vapour cavities within the bulk of a liquid flow when pressure drops below the vapour pressure at the local liquid temperature, in such areas due to the existence of impurities in the flow field or surface irregularities, phase-change takes place, initiating from either the material surface or inside the bulk of the flow. The bubbles produced may contain both vapour and non-condensable gas (i.e. air). Theses bubbles when advected to lower pressure regions, increase in size and if subsequently are brought abruptly into higher pressure regions in the flow, they collapse, during the collapsing process, their energy is transformed into pressure pulses which are emitted into the surrounding, causing material damage and erosion, mainly on non-deformable (metallic) surfaces. There is a substantial effort within the fluid mechanics community in developing a computational tool within the numerical algorithms currently used in cavitating flows, for predicting not only the location of the vapour bubble creation but mainly the region of its destruction, thus aiming into predicting the surface areas most prone to cavitation damage. Cavitation damage is considered to be caused by two fluid mechanics mechanisms: (1) either by the emitted pressure waves impinging on material surfaces during the bubble implosion and its subsequent rebound, according to Brennen and Leighton[1,2], (2) by the impulse momentum of a penetrating liquid micro jet impinging on the surface and which is created due to asymmetric bubble collapse near the surface and related to a hydraulic jump pressure Hammitt[3,4]. Kedrinskii[5], questions the potential of a single bubble collapse near a surface to create material damage as the amount of force that can be exerted on a surface by a single collapsing bubble is order of magnitudes smaller than the material hardness while in the case of the liquid micro jet impinging on the surface its kinetic energy is order of magnitudes smaller than the energy stored in the collapsing single bubble. According to Kedrinskii, it is the synchronous collapse of many bubbles which creates a cumulative pressure effect, above a threshold, which can initiate material erosion. Patella et al.[6-9] proposed an erosion model based on the pressure wave power density emitted by the imploding bubbles near a surface. The pressure wave energy emitted is obtained from the numerical solution of the Rayleigh-Plesset equation, with compressibility effe-

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cts taken into account, the time dependent wave energy results were then used for calculating the pit volume due to surface deformation of the material exposed to the pressure pulse, a linear relation was found with the coefficient of linearity depending on the material properties, the reliability of the model was also tested against experimental results on eroded samples of various metals with a good correlation. The wave power density, based on the maximum pressure emitted upon bubble collapse was found to be a good indicator of the erosion aggressiveness of the flow.

Franc and Mitchel[10] estimate the various pressures created upon bubble implosion and they conclude that the impacting pressure due to liquid micro jet may be of the same order of magnitude with the impacting pressure wave due to bubble collapse, however, its duration is orders of magnitude smaller, moreover, the mechanism of collapse of cavitating vortices, found in unsteady hydrofoil flows, is more important creating high impact loads, with order of magnitude higher duration, even higher than the collective synchronous bubble collapse. Dular et al.[11] conducted experiments in a water tunnel and presented erosion results on a cavitating hydrofoil at various flow conditions, the results obtained, mainly after visual inspection with the time of the eroded surface, were used to develop an erosion model based on the concept of the impulse pressure acting on the surface due to the liquid micro jet impingement upon asymmetric bubble collapse near the wall. The measurements indicate that erosion damage is related to cavity unsteadiness, while erosion aggressiveness is correlated to a power law of the nominal flow velocity, besides, increase of the non-condensable gas content in the water of the water tunnel reduces the erosion damage. The proposed erosion model correlates reasonably well, the impulse pressure created by the impinging liquid micro jet with the pit area created on the surface.

Dular and Coutier-Delgosha[12] used a CFD model based on RANS finite volume methodology for time dependent flows coupled with a barotropic model to account for cavitating flows, a modification was also employed to the k - ε RNG model for computing turbulent viscosity which takes in an heuristic way into account mixture compressibility, the CFD results were post processed and information about pressure distribution was coupled to the erosion model, proposed in Ref.[11]. The CFD methodology predicted the various phases of cavity cloud collapse, the associated pressure signatures in time and the resulting erosion as manifested by the formation of the pits in time. Even though the predictions are not very well correlated to measurements, the coupling of CFD post processing and the erosion model gives a direction for developing such an approach for engineering design. Terwisga et al.[13] reviewed the various erosion models reported in the literature and drew the conclusion that an initial bubble implosion synchronizes the implosion of a bubble cloud and that the synchronous implosion of many bubbles either per se or after breaking up of the traveling cavitation vortices may be the physical mechanism leading to cavitation erosion. Li[14] tested various erosion functions like pressure, partial derivative of pressure with time, the rate of change of volume vapour fraction and their time integrals based on CFD results after post processing. She concluded that the maximum rate of change of pressure in time is a better criterion for cavitation damage and it seems that high values of the rate of change of vapour volume fraction do not correlate with erosion damage. Li and Terwisga[15] investigated the time derivative of pressure as an erosion risk index in a flow around a hydrofoil at 8° angle of attack and concluded that an erosion intensity function which is the time mean value of the time derivatives of pressure above a threshold correlates well with the experimental evidence of erosion risk regions on the hydrofoil surface.

1. The cavitation aggressiveness index (CAI)

The paper proposes a methodology for predicting the region of bubble collapse and its cavitation aggressiveness. The idea for the proposed methodology is based on the concept that for a vapour bubble to collapse two conditions must be met: (1) the total derivative of the vapour volume fraction a must be negative (as bubbles must have decreasing volume) or equally the total derivative of the mixture density must be positive and (2) the total derivative of the pressure p must be positive (bubbles collapse at regions of increasing pressure),

$$\frac{\mathrm{D}a}{\mathrm{D}t} < 0 \tag{1}$$

$$\frac{\mathrm{D}p}{\mathrm{D}t} > 0 \tag{2}$$

The idea of using total derivatives (and not just partial derivatives) in estimating cavitation damage originates from the fact that bubbles at the final stages of collapse follow the streamlines due to their small size and collapse along them, the use of the total derivative makes the procedure applicable not only to unsteady but also to quasi steady-state flow calculations, flow regions of high positive total pressure, calculated with a steady-state RANS methodology, might be potential areas for cavitation damage in flows with intermittent cavitation regions, thus indicating secondary areas of cavitation damage. The previous two conditions, Eqs.(1) and (2), define a topology in the flow field where cavitation damage might appear.