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Relationship between material pitting and cavitation field impulsive pressures

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ABSTRACT

Material pitting from cavitation has been used on and off as an indicator of the vague concept of 'cavitation intensity'. Periodically, some researchers suggest the use of pitting tests as a means to provide quantitative measurements of the amplitude of the impulsive pressures in the cavitation field, especially when combined with Tabor's formula or with finite element computations with idealized synthetic loads. This paper examines the viability of such a suggested method using fully coupled bubble dynamics and material response, and strongly concludes that the method provides at best a qualitative assessment of the cavitation erosion potential. Peak pressures deduced from pit geometry are significantly lower than the ones actually applied. In addition the correspondence is highly dependent on the way the load is applied and different loading scenarios with the same amplitude of the cavitation impulsive pressure result in different pit aspect ratios.

1. Introduction

A material surface, which is exposed to cavitation, progressively erodes over time due to local high amplitude short duration and small footprint loads from repeated individual and collective cavitation bubble collapse [1]. Proper modeling of the physical phenomena at play is complex and requires understanding and description of both the two-phase fluid flow and the material dynamics as well as their interaction. Cavitation initiates from bubble nuclei in the liquid, which when exposed to low pressures grow explosively then collapse violently when the pressure recovers, thus generating very high local pressures and shock waves [1–4]. When a bubble collapses onto a material surface, a reentrant micro jet forms in the largely deformed bubble, vectors towards the material and impacts its surface with shock waves forming in the subsequent dynamics [5–9]. The flow due to the bubble collapse and the reentrant jet impact generate high impulsive stress into the material. When these exceeds the elastic limit of the material, permanent deformation occurs and a microscopic pit is generated [10]. This initial phase of material response to the cavitation field, the "incubation period", does not involve any mass loss. With repeated impacts, hardening of the material surface layer develops, which could be used for material peening [11,12], then pits accumulate and finally micro-failures occur resulting in material removal and weight loss.

In order to characterize cavitation erosion for different cavitation conditions (e.g. different flow field velocities, or comparison between small scale laboratory accelerated erosion tests and full scale conditions), a well-defined method to characterize the intensity of the cavitation flow field at the exposed material surface is needed. Pressure transducers are the obvious first choice, but they have limitations due to their size, which is often much larger than the cavitation bubbles, and their resonance frequency, which is often lower than the required high frequency pressures generated by the small microbubbles [1,13]. Another method, which has been periodically proposed during the past century, is to conduct pitting tests. In this case, short duration cavitation tests are conducted within the incubation period where non-overlapping pits are produced. These pits are then measured and characterized to deduce from their distribution and geometry the hydrodynamic flow field pressures (e.g. [3,14–16]). Cavitation pitting studies dates back to the early 1900's when Parsons and Cook [17] observed the depth and dimensions of the pitted areas on marine propellers. Since then, many researchers have tried to correlate the location of pitting with cavitation bubble clouds along with statistics of pit number and pit diameters and depths [2,18–24]. More recently, pitting tests were also conducted using thin copper foil in order to capture relatively small magnitude impacts [25]. With the advances in modern imaging and micro-measurement techniques, recent studies reveal

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more details of the pit shapes and pit statistics [1,26]. All these studies, however, did not use or provide direct quantitative relationships between the cavitation field pressures and the generated pits.

More recently, there have been renewed effort to correlate the cavitation field impulsive pressure and the measured pits characteristics [7,27,28], in which attempts have been made to correlate the experimentally measured ratios of pit depth to diameter to the pressure filed using the spherical indentation relationships developed by Tabor [29] and making, without real justification, the major assumption that spherical indentations (rigid load/material interface and strain rates, $\sim 0.05\ \mathrm{s}^{-1}$) and collapsing bubbles (deforming liquid/material interface and strain rates, $\sim 10^4\ \mathrm{s}^{-1}$) produce similar loads on the material. An effort to include the strain rate dependency of the stress–strain curves was attempted in [28] but static loads only were still considered. Recently, finite element method analysis was also conducted [30–31] using the same basis for the load as in the Tabor approach, i.e. time independent idealized constant pressure load, and obviously, due to the over-simplified parameters, an almost one-to-one relationship between the loads and the pit geometry characteristics was found. The time dependent analysis in [32] confirmed that such one-to-one relation is achieved only when the time scale of the load is larger than $10^5\ \mu\mathrm{s}$ (see Fig. 5 of [32]), which is huge compared to the duration of bubble dynamics generated peak pressures.

The believers in the pitting technique claim that the method allows the material to be used as a high fidelity recorder of the cavitating field pressures and that the results would be independent of the material used [16,27,31]. Actually, a first strong limitation of this statement is that only pressures that lead to stresses higher than the elastic limit of each particular material will form pits and all lower pressures cannot be measured. Thus, each material acts as a high pass filter and records only the pressures above a cutoff value, which is material dependent. Other even more significant limitations are examined in more details in this paper using advanced bubble dynamics-material dynamics interaction modeling techniques [7,8,33] and stem from the examination of the quantitative relationship between pit characteristics and actual dynamic pressure loads.

In order to investigate this relationship, a numerical fluid-material interaction approach is undertaken to investigate pitting formation from the combined bubble dynamics and material mechanics viewpoints. Fully coupled Fluid Structure Interaction (FSI) simulations are conducted and provide both the actual liquid generated pressures and the resulting material pit characteristics. Using these results, the actual pressure applied on the material surface is compared with the one deduced from the pit geometry using the Tabor equations [29]. The same approach is also applied using synthetic loads (prescribed loading, no FSI) as published in previous work [30–33] where the applied load is specified and the resulting material pits deduced and the results compared to the Tabor predictions.

2. Material/Fluid interaction simulations

In this study, correlation between the cavitation pressures in the liquid and the resulting pit characteristics is studied using FSI coupled material finite element method simulations with fluid dynamic simulations of bubble collapse of various intensities. We describe briefly below the methods used and refer the reader to much detailed descriptions in Refs. [7–9] as well as other references cited below.

2.1. *Bubble dynamics*

The numerical approach applied to model material pitting is part of a general hybrid FSI approach we developed to simulate fluid structure interaction problems involving shock and bubble dynamics encountered in cavitation and underwater explosion bubbles [34–37]. During a major portion of the bubble growth and collapse history, the velocities in the liquid are much smaller than the liquid speed of sound, and an incompressible approach is justified. A potential flow boundary element code, 3DynaFS-Bem© [34,35,38] is used during this time period. On the other hand, shock waves and strong compressibility of the liquid come into play during the last stage of the bubble collapse and following reentrant jet impact on the material. A time decomposition approach is then used to switch for the incompressible solution to fully compressible solvers such as Gemini [36] or 3DynaFS-Comp© [39]. This time decomposition hybrid procedure combining incompressible and compressible solvers to capture the full dynamics has been described in details in [37]. The procedure takes advantage of the capabilities of 3DynaFS-Bem©, to produce very accurate capturing of the reentrant jet [40], and Gemini and 3DynaFS-Comp©, which have been proven very good at capturing shock dynamics and resulting pressures on the boundaries [41]. Description of both methods and the coupling procedure can be found in [35,39]. Illustrations of the results are shown later below.

2.2. *Material response*

The dynamics of the material is modeled by the finite element model Dyna3D, which is a non-linear explicit structure dynamics code developed by the Laurence Livermore National Laboratory [42]. The US Navy version used in this paper is named DynaN. The structural code computes the material deformation with the loading being provided here by the fluid solution (either 3DynaFS-Bem©, 3DynaFS-Comp©, or Gemini). DynaN uses a lumped mass formulation for efficiency. This produces a diagonal mass matrix **M,** to express the dynamics equation as:

$$\mathbf{M}\frac{d^2\mathbf{x}}{dt^2} = \mathbf{F}_{\text{ext}} - \mathbf{F}_{\text{int}}, \tag{1}$$

where $\mathbf{F}_{\text{ext}}$ represents the applied external forces, and $\mathbf{F}_{\text{int}}$ the internal forces. The acceleration, $d\mathbf{x}^2/dt^2$, for each element is obtained through an explicit temporal central difference method. Additional details on the general formulation can be found in [42].

2.3. *Cavitation and material interactions*

Material-fluid interaction effects are captured in the simulations by coupling at each computation time step the fluid codes and Dyna3D using a coupler interface. The step-by-step coupling is achieved by following the numerical procedure below:

Step 1: The relevant fluid code computes the pressures at all material surface nodes.
Step 2: In response to this pressure loading, the material code computes material deformations, stresses, strains, and the surface node velocities.
Step 3: The coordinates and the velocities of the material surface nodes then define new boundary conditions for the fluid code at the following time step.
Step 4: The relevant fluid code then solves the flow field using the material surface node positions and normal velocities and deduces the liquid pressures at the material surface for the next time step, looping back to **Step 2**.