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Determination of cavitation load spectra – Part 1: Static finite element approach

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ABSTRACT

Numerical prediction of cavitation damage strongly relies on the determination of the loading conditions applied to the wall. In this paper, an inverse method is proposed to identify the pressure field that could generate individual pits as observed experimentally on eroded samples of Aluminum alloy 7075-T651. The pits are defined by the diameter and depth of the imprints. Assuming each pit was generated by a single bubble collapse, the pressure load is defined by two parameters, the peak pressure (σ_H) and its radial extent (r_H). Two methods are proposed based on finite element modeling. The first one uses analytical expression of the unknown parameters built from a parametric simulation campaign. The second one is based on an optimization loop of the finite element simulations to best fit the experimental measures for a given error limit. Both methods give access to the load distributions relevant to the flow aggressiveness of the cavitation test.

1. Introduction

It is well-known that the repeated collapse of cavitation bubbles may erode solid walls [1–3]. The collapse of a cavitation bubble is generally associated with the formation of a micro-jet and/or shock waves, which impact the nearby solid surface resulting in a cavitation pit, if the load is high enough to exceed the local yield strength of the material. In order to predict the erosion damage including the long-term damage and mass loss, it is essential to know the loading conditions generated by bubble collapses and analyze the response of the material to these loads.

The determination of the loading conditions due to the combined or solo effect of micro-jet and shock waves during cavitation bubble collapse is a major issue in cavitating flows. Numerical approaches may be used to compute the pressure pulses due to the collapse of a single bubble or bubble clusters that may develop in real flows such as the flow around a cavitating foil or in a cavitating hydraulic device (see e.g. [4–6]). The difficulties in such approach arise from the complex fluid-structure interaction and also from the large number of parameters involved on the fluid side such as bubble content, bubble size, distance to the wall, pressure history to which the bubble is subjected, potential interactions between bubbles, etc.

Pressure pulses may also be measured in cavitation facilities. One option is to use pressure transducers flush mounted in the region of bubble collapses. The pressure signal generally shows successive pulses of various amplitudes caused by bubble collapses [7–9]. This method allows determination of impact loads in force units (typically in Newton) but the determination of the pressure or stress amplitude (in MPa) is difficult because the loaded surface area is unknown and usually much smaller than the transducer sensitive surface. Moreover, conventional pressure transducers, because of their limited natural frequency, may not capture accurately the cavitation pressure pulses whose rise time and duration are quite small. Finally, the impact could plastically deform or even damage the transducer leading to faulty responses.

In order to overcome these measurement difficulties, another option may be used. It consists in using the material itself as a transducer. The measuring technique is based on pitting tests as introduced by [10,11]. The idea behind pitting tests is that each pit is the signature of a single bubble collapse. Then, it can reasonably be expected that the loading conditions be derived from the geometry of the pit and the material properties.

Such a technique has been used by [12,13]. The authors have taken advantage of the similarity between a cavitation erosion pit and a spherical nanoindentation to estimate the amplitude of the pressure pulse responsible for a cavitation pit. The method is based on the use of Tabor's equation [14] that makes it possible to estimate the mean strain associated to a plastic deformation of given depth and diameter. It is easy to deduce the stress from the estimated strain using the stress–strain relationship of the material.

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Nomenclature

r	Radial direction for an axisymmetric element
z	Longitudinal direction for an axisymmetric element
R	Maximum radial size of the simulated volume
H	Vertical size along z-axis of the simulated volume
σ_H	Peak pressure of hydrodynamic impact
r_H	Radial extent of hydrodynamic impact
d_H	Diameter of hydrodynamic impact
h_P	Pit depth
d_P	Pit diameter at 50% of pit depth
r_P	Pit radius at 50% of pit depth
h	Depth (Eq. (6))
d	Diameter (Eq. (6))
h_{max}	Maximum pit depth (Eq. (6))
d_{max}	Maximum pit diameter (Eq. (6))
P_0	Maximum Hertz pressure
r_c	Hertzian contact radius
T	Shear stress along depth, z on the axis of symmetry
σ	True stress
ε	True strain
$\dot{\varepsilon}$	Strain rate
σ_y	Elastic limit
m_y	Parameter of the Ramberg–Osgood constitutive equation
K_y	Parameter of the Ramberg–Osgood constitutive equation
ε_e	Elastic strain
ε_P	Plastic strain
σ_u	Ultimate stress
ε_u	Ultimate strain
E	Young's modulus
ν	Poisson's ratio
k	Material constant (Eq. (3))
N	Cumulative pitting rate
h_c	Cut-off depth (Eq. (7))
$\sigma_{H_{min}}$	Minimum value of peak pressure require to form a pit (Eq. (7))

In the present work, another technique is investigated for deriving the loading conditions from pitting tests conducted during the incubation period. It is based on finite element (FE) computations of the response of the material to a representative pressure pulse. The pressure pulse considered here has a Gaussian shape and is defined by two parameters, namely its maximum amplitude and radial extent. The Gaussian shape profile used for the FE simulations is found to produce non-dimensional pit shapes that are close to that experimentally observed, as discussed in Section 4. An inverse technique is proposed to derive these two parameters from the depth and diameter of the pit, both deduced from an appropriate analysis of the pitted surface.

This kind of approach, combining FE simulations and pitting test is relatively new and the authors have noticed only few publications. To our knowledge, such an inverse technique has only been used by Phol et al. [15] using a different bell-shape pressure profile into the framework of static FE (no time dependencies) analysis of material response using 2D axisymmetric modeling. We are proposing here a simple and fast technique based on interpolation that optimizes the pressure parameters for given error limits in pit dimensions. Moreover, we show that a given pit shape could be optimized with a unique set of parameters for the assumed pressure profile. Note that in order to simplify the problem, Phol et al. [15] have ignored dynamic effect that include inertia and strain rate sensitivity of the material, as we are doing in this current Part 1 paper.

The event of cavitation hydrodynamic impact is very dynamic in nature since the impact duration is very short, in the order of a microsecond, as observed experimentally and/or by computational fluid dynamics (CFD) simulation of cavitation bubble collapse [5,16–19]. In a companion paper (Part 2) [20], we have performed dynamic explicit FE analysis of the cavitation impact using similar Gaussian pressure field with a temporal evolution of Gaussian type. By decoupling the effect of inertia and strain rate sensitivity into the simulation, it was found that for impact duration of 1 μs or more the inertial effect becomes insignificant and, static and dynamic explicit FE analyzes yield the same solution in terms of resulted pit dimensions. Similar observation was reported by Choi et al. in [19]. However, strain rate effect at such high rate of loading in cavitation pitting cannot be avoided if the material is strain rate sensitive. For more details see [20], where it is shown that for duplex stainless steel (A-2205) which has high strain rate sensitivity, although inertial effect is negligible for impact durations as small as 1 μs, the dynamic effect associated with strain rate sensitivity is unavoidable till 10^5 μs (or 0.1 s) of impact duration; thus care should be taken as described in [20]. In order to avoid the effects of strain rate in our modeling approach, the current study is conducted on Aluminum alloy 7075-T651 (Al-7075) which has very weak strain rate sensitivity [21] so that a static approach appears fully appropriate for this particular alloy even for impact durations as short as 1 μs.

The strain rate sensitivity coefficient of Al-7075 was estimated by using the well-known Johnson-Cook plasticity model, for which compression and Split Hopkinson Pressure Bar (SHPB) tests were done for strain rates ranging from 0.001 to $\sim$2000 s^{-1}, details of which can be found in [21]. A value $C = 0.0068$ for the strain rate parameter was found which demonstrates negligible strain rate sensitivity.

Although in the current study, static analysis was adopted for the inverse FE technique, it is shown in Part 2 [20] that this inverse technique could be transposed to dynamic explicit analysis as well and then applied to strain rate sensitive materials by considering the complete dynamic behavior including inertia and strain rate sensitivity. The question of impact duration corresponding to each cavitation pit remains however unsolved. The authors [5,16,17] have both experimentally and numerically determined the impact durations corresponding to cavitation bubble collapses. However, the geometry and the cavitation conditions considered in these studies are significantly different from the conditions considered in the present paper, so that the transposition of these data to the present case is not straightforward. To our knowledge, the impact duration cannot be determined from the sole pit shape that represents the final plastic deformation and time sensitive transducers are required to provide details on the time evolution of the impact load including its duration. In the case, the impact duration is unknown; it may be difficult to use a fully dynamic approach. For strain rate sensitive material, one option could be to use a static approach and extrapolate the material properties to a high strain rate that would correspond to the typical strain rates involved in cavitation impacts (for more details see [21]).

The inverse FE technique has been implemented in [21] for different cavitation flow conditions and impact loads were estimated by using three different materials as sensors. Very interestingly, statistical analyses of the estimated impact loads show a material independent response for a given flow condition. This is