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Phenomenological prediction tool for cavitation erosion fed with the International Cavitation Erosion Test results

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ABSTRACT

Foundations of methodology and the calculation tool for prediction of cavitation erosion performance of elasto-plastic materials are presented. Probabilistic phenomenological model for quantifying the process and experimental results of the International Cavitation Erosion Test were used to develop the tool as an application of the erosion prediction method. It comprise implementation of the model accompanied with phenomenologically derived formulas for discovering the parameters included. Necessary input data to its activation refer to loading value and target specifications, including strength parameters of the material. Having been completed, the system may serve as a tool for simulations of the cavitation erosion performance as solid volume loss in the time domain.

1. Introduction

Cavitation erosion may be a vital problem in many liquid-flow systems, such as ship propellers, hydraulic turbines or valves, being a reason of major concern for hydraulic equipment designers and users. The developed process leads to decrease in efficiency of operating machines and the need of frequent maintenance and repairs. The resulting costs comprise performance and availability losses due to machine outage. Therefore, the reliable tool to predict the risk of cavitation erosion is welcome.

In the paper foundations of the system for prediction of cavitation erosion performance of elasto-plastic materials are presented. Probabilistic phenomenological model for quantifying the process and experimental results of the International Cavitation Erosion Test (ICET) [1,2] are used to develop the computational tool: numerical implementation of the model accompanied with phenomenologically derived formulas for discovering the parameters included. Necessary input data to its activation refer to loading conditions – power flux density and target specifications, including physical/strength parameters of the material. As a result, erosion performance - the time evolution of the volume loss of material exposed to cavitation is obtained. In this way, appropriate simulations of the process are also possible.

The aim of the work is to present the methodology for prediction of material volume loss in the process of random impact loadings by using the phenomenological model of minimum number of parameters and its practical implementation based on the ICET results. An approach presented herein is the problem oriented extension of the method described previously in [3] built on the assumption on proportionality of volume loss to the difference of the rates of the energy supply to the surface layer and the energy used for crack closure process, as well as other geometrical/environment processes participating in retarding the cracks development. Eventual numerical implementation of the submitted solution makes it an effective calculation tool for prediction of cavitation erosion of materials within the MDPR (mean depth of penetration rate) range confined approximately between the values specific for pure alumina and hardened martensitic steels.

The scope of the work covers presentation of the simulating model supplemented with the formulas for calculation of model equations parameters. The latter stand for the dependencies on physical/strength parameters of the material and have been derived by phenomenological procedures. Moreover, preliminary experimental verification of the simulating capabilities with respect to cavitation erosion of some materials not included in the ICET investigations was carried out. The reliability of the system and sources of uncertainties are also discussed.

2. Specific nature of the process and approaches to prediction of cavitation erosion performance

According to standardized description of the phenomena, surface damage of materials placed within the collapse zone of a cavitation cloud occurs under the action of forces arising from

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bubble implosions, occurring as collective or uncorrelated events. Specifically, cavitation erosion depends on the type of the loading cloud, its spatial distribution, average pressure, dynamics of local forces, amplitude and probability mass function of pulses, surface morphology of the solid, its chemical composition, microstructure, physical state (e.g. residual stress), and resulting strength parameters. Moreover, when thin coatings are under consideration, the dependence of the process on solid geometry should not be neglected. It seems that cavitation erosion should be dealt with as an autonomous type of material damage due to the peculiarities of cavitation loading: short impact time, comparable to relaxation period of viscous volume forces of fluid [4], infinitesimal area of impact action, and the randomness of the impingements, allowing for a large number of different destruction mechanisms occurring at the same time. The initial stage of erosion is featured by accumulation of internal stresses and deformations, without discernible volume loss. Indentations are formed due to local, plastic deformations in the surface layer. The process is accompanied by cracking and extracting the material pieces. Cracking under external loading is initiated at the target surface but nucleation and coalescence of micro-cracks runs within deeper layer of the material as well. An increase in micro-cracks density is driven by subsequent impulses until the extraction of the material piece occurs. The assumption on paramount role of the micro-cracks may be linked to high rate of the loading force cycles and fatigue nature of the process.

In predominant number of cases cavitation erosion process is of fatigue nature: it has been established that cavitation damage is strongly correlated with fatigue strength of the material [5–8]. Besides, there are some results that support this opinion in an indirect way [9–11]. Fatigue-like erosion within an incubation period follows Miner's law of impact loads, regardless of the cavitation conditions and the materials [12]. On the other hand, a parallel occurrence of the disintegration and inhibiting processes determine the existence of the hardening regime. Especially, if hardening ability leads to significant increase in the local brittleness one can refer the process to work hardening regime. An influence of the hardening ability on cavitation erosion performance has been confirmed experimentally, i.a. in [13]. Due to the nature of the process, only pulses with amplitude exceeding a certain threshold value contribute to fatigue damage of the material surface layer [14,15]. Substantial diversity of the erosion performance of the particular material samples under same loading energy flux is due to random nature of the process, including stochasticity of the initial conditions (e.g. [16]). Then, the precise prediction of the cavitation erosion progress is a challenging task due to the high sensitivity of the process, which is proven by the enormous scatter of the mass loss recorded in different experimental tests conducted at conditions differing only by quality characteristics of the loadings [1]. The latter may be a result of not appreciated factors, which sometimes induce synergic effects. For example, enhancement of the cavitation erosion by hydrogen corrosion was considered in the works [17,18].

Quantification of material damage under cavitation loading consists in assessing surface changes in the initial period of the process or measuring the kinetics of material volume loss in the advanced stage of the erosion which allow to obtain a cumulative erosion characteristics. Both the loading conditions and temporary physical properties of the impinged solid surface should be taken into account in the quantitative description of the process that may be considered stationary only in a probabilistic sense. The influence of various determinants and properties on material performance was investigated by numerous researchers, e.g. [13,19–24].

Numerous efforts of modeling the process with its complexity have been taken from various standpoints (e.g.[25–35]). Some contemporary works model cavitation impingements action and resulting erosion by employing the material and processing parameters in formulas derived from model assumptions, e.g. based on fatigue nature of the damage (e.g. [36]), without confining its applicability to the incubation period of the erosion. Prediction of cavitation erosion efficiency in defined environmental conditions may consists in using the relevant scaling laws. There were some attempts to do so (e.g. [37–41]), especially to find a dependence of the erosion intensity on fluid velocity, geometric length scale and acoustic impedance of the liquid. The search for relevant physical parameters of the impinged material – factors affecting its erosion resistance – may be complementary to modeling the erosion process [42].

However, solution to such problems as prediction of erosion progress or distinguishing the features decisive for cavitation resistance at given erosion stage and conditions fully satisfactory for all cases met has not been found yet. On the other hand, none of the systems known may be regarded sufficiently precise and convenient for engineering practice. To build up the simulator for practical purposes the following imperatives and premises should be accounted for:

(1) Strictly theoretical modeling of the process on ground of the conservation equations is not prospective due to high complexity of the problem, especially extremely high deviation from equilibrium conditions and non-linear dynamics of material shear as well as the range of physical quantities variability. Physical parameters characterizing material element change under cavitation loading.
(2) Simulation of the process at sub-nanometric or microscopic level is also impossible because of such sources of uncontrolled ambiguities as multiplicity of the destruction mechanisms and the need for precise modeling of the field of internal forces due to a single cavitation impulse, randomness and multidirectional orientation of the forces and problems in interpreting correlation of the damage advances with material microstructure.

3. Prognostic system – conception and logic

Prediction of a random volume loss process is based on phenomenological model of low number of parameters, disregarding the space resolution of the damage topography. It is a simplified version of the model of 14 parameters presented in [3]. Calculation parameters are related to strength parameters of the material by functional relationships derived phenomenologically. The results of the International Cavitation Erosion Test were the source of required experimental data. Methodological concept consists in adjusting the theoretical erosion curves to experimental ones by variation of the parameters values for five materials differing substantially in their strength properties. Matching the calculation and strength parameters was expected to reveal the functional relationships between them, if such exist. The procedure carried out started with adjustment of calculated erosion curve to experimental one for each individual case by appropriate selection of calculation parameters. Having the calculation parameters found, their functional relationships to physical/strength parameters of the materials were established.

Numerical implementation of the model completed with the derived functional relationships is a tool enabling a prospective user to predict the material performance under defined cavitation loading. The approach is valid under assumption that defined relationships are independent on the type and amplitude of the loading, i.e. on the testing set-ups.