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A PROCEDURE TO ACCOUNT FOR OVERLAPPING IN PITTING TESTS

Thierry CHOFFAT / LEGI-CNRS-INPG
thierry.choffat@hmg.inpg.fr

Regiane FORTES PATELLA / LEGI-CNRS-INPG
fortes@hmg.inpg.fr

Jean-Pierre FRANC / LEGI-CNRS-INPG
jean-pierre.franc@hmg.inpg.fr

Antoine ARCHER / EDF-R&D
antoine.archer@edf.fr

ABSTRACT

An experimental methodology for cavitation damage measurements based on a 3D laser profilometry technique has been developed by the LEGI and EDF (Electricité de France – R&D Division) [1,2]. Previous works pointed out the strong influence of the test duration and the analysis cut-off parameters (related to the measurement resolution threshold) on the evaluation of the volume damage rate "Vd" and of the pit number rate "Nd" obtained experimentally during the incubation time of the cavitation erosion mechanism.

In order to evaluate and rectify the influence of the test duration on the cavitation damage measurements, a software was developed to simulate the generation of cavitation impacts on a solid surface. From a single reference test concerning a material, a given cavitation condition and a test duration, the software predicts the damage of other materials exposed during different durations to the same cavitating flow.

Numerical simulations were compared to experimental results observed on some sample surfaces (copper and aluminum) damaged in the EDF Modulab test loop under different flow conditions.

INTRODUCTION

The understanding of the cavitation erosion phenomenon and the prediction of material damage remain a major challenge for scientific researchers and machinery manufacturers.

The difficulties to carry out experimental studies and physical local analysis of the cavitation damage mechanisms are related mainly to the magnitude of the characteristic scale of the phenomena: the pressure impact amplitudes are supposed bigger than 1 GPa, the impact durations varying between 10 ns and 1 µs, and length scale are the order of 10 µm.

From these considerations, based on an initial Knapp's idea [3], many authors have developed experimental, theoretical, and numerical works by using the material as a sensor to try and evaluate the cavitation aggressiveness of the flows [1,2,4-18]. Many of these works applied pit counting techniques and/or cavitation damage measurement methods to estimate impact densities on material surfaces damaged by cavitation during incubation period. This period corresponds to a short exposure time of the solid samples to the cavitating flow and the damages observed on the solid surface are only material plastic deformations (named pits or indentations), without mass loss or fracture.

In those studies, cavitation intensity was estimated from the volume damage rates "Vd" and/or from pit number rates "Nd". Results obtained were often applied to analyze the influence of mean flow velocity, geometric scale or solid characteristics on the cavitation erosion phenomenon [6, 8, 10, 17, 19].

In this context, we have developed an experimental methodology to measure cavitation damage based on a 3D laser profilometry technique [1]. A software for automatic analysis of the sample surfaces pitted by cavitation was also developed and used to treat several experimental results concerning copper, stainless steel and aluminum samples [2, 17, 18]. These previous works pointed out the strong influence of the test duration (Figure 1) and the analysis cut-off parameters on the evaluation of the damage rates "Vd" and "Nd". Indeed, whatever the applied technique is, the quality of the obtained results is strongly related to these experimental and analysis parameters.

The influence analysis of the cut-off parameters was presented in detail in [1]. The aim of the present paper is to propose a method of evaluation of the test duration influence on the cavitation mark measurements and, consequently, on the estimation of flow aggressiveness.

NOMENCLATURE

E_{wave}^{mat}	pressure wave energy	[J]
H	pit depth	[µm]
Nd	pit number rate	[pits/mm^2/s]
P_{wave}^{mat}	pressure wave power	[W]
$R_{10\%}$	pit radius at 10% of H	[mm]
T	test duration	[s]
v	flow velocity	[m/s]
V	pit volume	[µm^3]
Vd	measured volume damage rate	[µm^3/mm^2/s]
V^d_e	volume damage rate corresponding to ΣV_e	[µm^3/mm^2/s]
V^d_m	volume damage rate corresponding to ΣV_m	[µm^3/mm^2/s]

β mechanical characteristic coefficient [J/mm^3]

ΣV_e total simulated volume [µm^3]

(without pit overlapping). This parameter corresponds to an "effective energy" applied to the solid surface, which is responsible to the measurable volume damage

ΣV_m total measurable volume simulated on the material surface due to the "effective energy" applied to the solid surface [µm^3]

(it includes pit overlapping). This parameter will be compared to the volume damage obtained experimentally (corresponding to Vd).

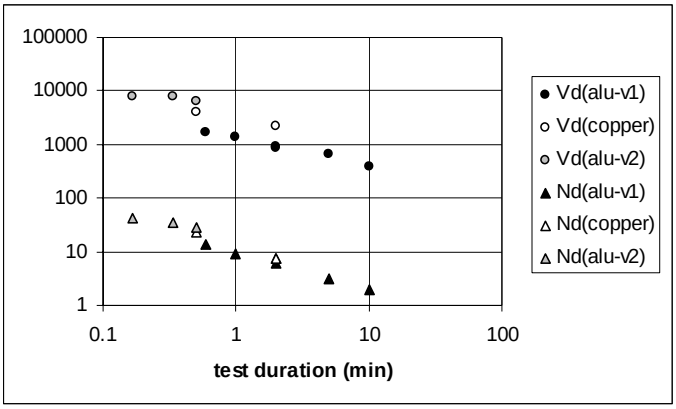


Figure 1: Volume damage rate V_d (µm^{3}mm^{-2}s^{-1}) and pit number rate N_d (×10^{2}pits.mm^{-2}.s^{-1}) as a function of test duration for copper (v = 38.5 m.s^{-1}) and aluminum samples (v_1 = 20 m.s^{-1} & room temperature ; v_2 = 32 m.s^{-1} & 30°C) [1]

HYPOTHESIS

This work is based on some previous studies and applies many results obtained before [2, 17, 18, 20]:

- indentations are supposed to be generated by the impact of high amplitude pressure waves emitted during spherical bubble collapses;
- the pressure wave responsible of the damage is characterized by the energy E_{wave}^{mat};
- indentations are considered axisymmetric. They are characterized by the maximum depth H, the radius $R_{10\%}$ at 10% of the depth, and the pit volume V, as illustrated by Figure 2;
- the profile of the pit can be deduced from H and $R_{10\%}$ thanks to a previous numerical study [17] that pointed out the polynomial aspect of the non-dimensional profile of the pit (Figure 3).
- the pit volume and the pressure wave energy are related thanks to the mechanical parameter β by the relation:

$$V = \beta^{-1} E_{wave}^{mat}$$

- the flow aggressiveness is characterized by the pressure wave power P_{wave}^{mat};
- material damage is evaluated by the volume damage rate Vd and by the pit number rate Nd.

1. EXPOSURE TIME AND OVERLAPPING OF IMPACTS

In a previous study [1], experimental tests were performed in the EDF Modulab test rig in order to evaluate the influence of exposure time on the measured damage rates. The strong influence of test duration was then pointed out, both for the pit number rate N_d and the volume damage rate V_d (Figure 1). This decreasing tendency can be explained by the overlapping of impacts as time goes. Indeed, let β be the ratio between the volume generated on a sample by a pressure wave and the energy of this pressure wave. Previous study [21] showed that β is much bigger for isolated impacts (that is a single pressure wave interacting with the sample) than for overlapped impacts (that is a pressure wave striking a previously damaged zone of the sample) as illustrated on Figure 4. This is due to the work-hardening of the material: residual plastic strains strengthen it.

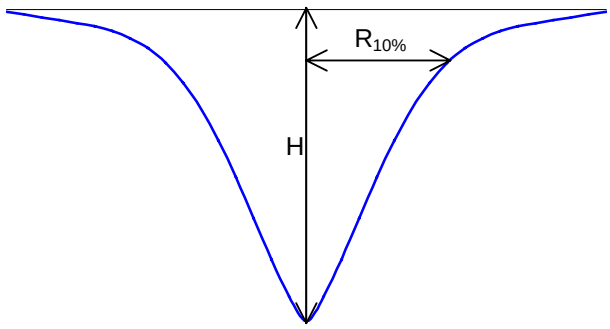


Figure 2: Axisymetric profile of an isolated pit

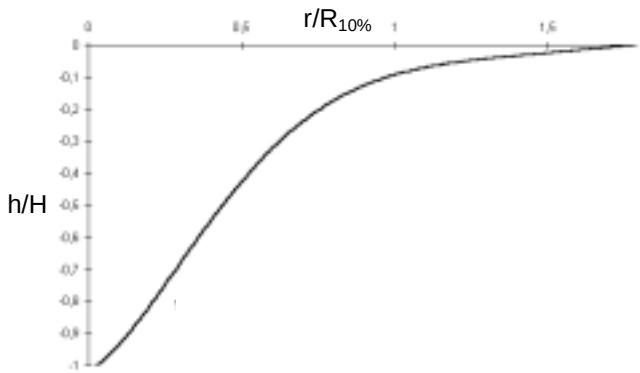


Figure 3 : Non-dimensional profile of a pit, where h is the local depth, and r the local radius. The coordinates are cylindrical axisymmetric and only one meridian half plane is presented. From [17].

Consequently, the damaged volume (and the rates N_d and V_d) will depend on the overlapping of impacts, and thus on test duration. If an experiment would last too long, the overlapping of impacts would lead to the saturation of the whole strengthened sample, and linking the damage rates to the flow aggressiveness would no more be possible. As a consequence, short duration tests are favored, but exposure time remains a

parameter that needs to be taken into account in order to correct the evaluation of the flow aggressiveness. The next section will present the tool that has been developed in order to reach this aim.

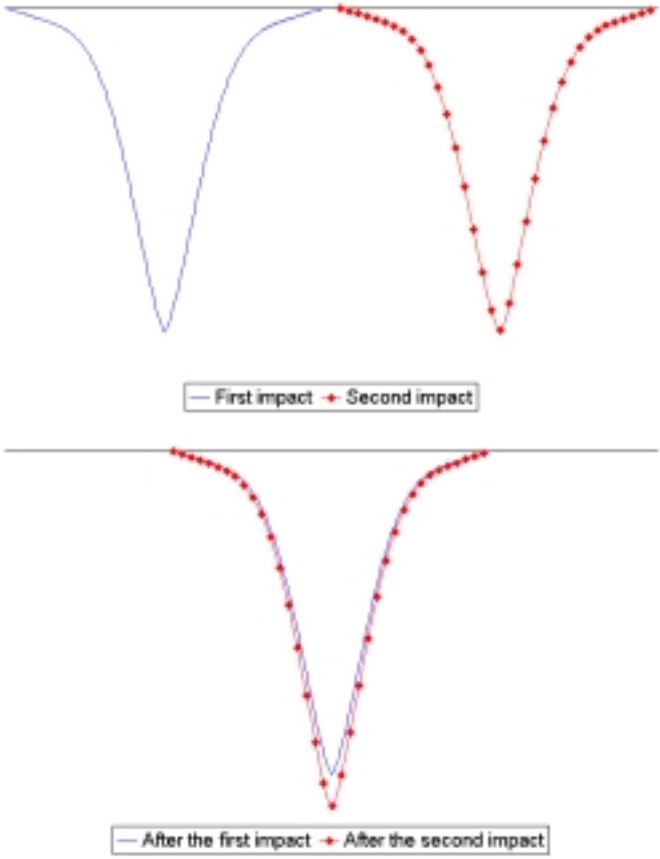


Figure 4: Qualitative comparison between the volumes damaged by two identical pressure waves in two cases. If the indentations remain isolated (above), the total volume is twice the volume of a single indentation. If the impacts overlap (below), the total volume is lower than twice the volume generated by the first pressure wave. From [21].

2. EXPOSURE TIME CORRECTION

2.1. The "constant power" hypothesis

Let us consider a sample exposed to a given cavitating flow. The collapse of cavitation bubbles generates pressure waves that interact with the material. This interaction can be seen as follows for a single isolated impact:

- a pressure wave, characterized by an energy E_{wave}^{mat}, impacts on the material. This impact generates a pit in the sample (the volume of this pit is V).
- previous studies [2,20] showed that the pit volume could be related to the energy that generated it by relation $V = \beta^{-1}E_{wave}^{mat}$, where β is a constant characteristic of the material (for an isolated impact).

For a given cavitating flow, the hydrodynamic conditions are constant, and thus the erosive power P_{wave}^{mat} can be supposed constant (equivalently, the total energy ΣE_{wave} penetrating the sample can be supposed proportional to exposure time). Consequently, if one considers a test duration T during which the total energy penetrating the sample is $\Sigma E_{wave}^{mat}(T)$, one can distinguish two situations:

- in an ideal situation, all the impacts would remain isolated, and the relation $V = \beta^{-1}E_{wave}^{mat}$ would be applied to each pit. The total damaged volume, called $\Sigma V_e(T)$, is thus:

$$\Sigma V_e(T) = \beta^{-1}\Sigma E_{wave}^{mat}(T).$$

This volume is the maximum damaged volume that can be generated by the energy $\Sigma E_{wave}^{mat}(T)$ because there is no overlapping between the impacts. The suffix "e" means "energetic", because this volume is associated to an energy

- in reality, the different impacts can be overlapped, and the total damaged volume that one can measure is inferior to $\Sigma V_e(T)$ for the same energy $\Sigma E_{wave}^{mat}(T)$. This total volume is called $\Sigma V_m(T)$, where the suffix "m" means "measurable".

As the erosive power is supposed constant for a given cavitating flow, one can write for two exposure durations T_1 and T_2:

$$P_{wave}^{mat} = Cte = \frac{\Sigma E_{wave}(T_1)}{T_1} = \beta\frac{\Sigma V_e(T_1)}{T_1} = \beta\frac{\Sigma V_e(T_2)}{T_2}$$

which leads to :

$$\Sigma V_e(T_2) = \frac{T_2}{T_1}\Sigma V_e(T_1)$$

We can deduce from this relation that the total volume $\Sigma V_e(T_2)$ can be calculated for every exposure duration T_2 from a single total volume $\Sigma V_e(T_1)$ that remains to be evaluated, but that no link can be found between $\Sigma V_m(T_1)$ and $\Sigma V_m(T_2)$, if $T_1 \neq T_2$. Thus, the study will be developed in terms of $\Sigma V_e(T)$.

Hence, the volume damage rate V_e^d (respectively V_m^d) can easily be deduced from a total volume $\Sigma V_e(T)$ (respectively $\Sigma V_m(T)$) by dividing it by the test duration T and the scrutinized surface.

2.2. THE CALCULATION PROCEDURE

An Excel calculation code, based on the procedure presented here above, has been developed in order to:

- take into account the test duration in the evaluation of the aggressiveness of the flow during incubation time
- simulate the mass loss period.

Only the incubation period will be treated in this paper.

2.2.1. SIMULATION OF THE PITS

In the 3D experimental analysis method used by LEGI and EDF (R&D) [1,17], histograms summing up the characteristics of the pits are obtained. These histograms provide the number of pits as a percentage of the total number classified according to the pit depth and pit radius (Figure 5).

Histograms indicate the frequency of indentations that are characterized by a couple $(H,R_{10\%})$. Along the simulation, we can find the most probable indentation to generate at a given

moment, which allows the program to simulate pits in the same proportions as those indicated by the histogram.

The simulated pits are then placed on an Excel sheet that represents the simulated sample. The value of a cell corresponds to the depth of an elementary surface area. The step between two cells is 4µm, so the elementary surface areas are 16µm². The simulated sample is 1mm in width, and can be chosen between 1 and 250mm in length.

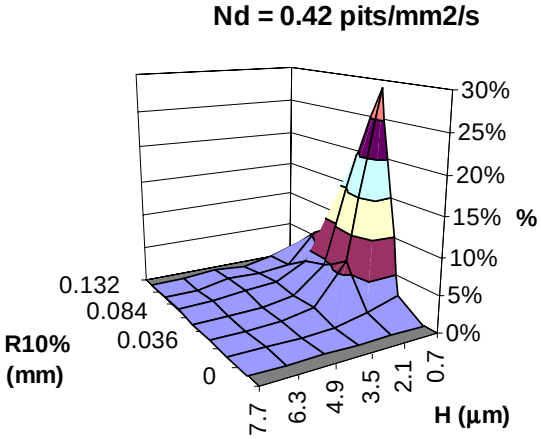


Figure 5: the histogram illustrates the ratio between the number of pits for each class of depth "H" and radius "R10%". Aluminum sample; v=32m/s; water at 30°; T=10s

The random aspect of the simulation comes from the location of the pits. In order to place an indentation, the position of the pit center is chosen with a random and homogeneous repartition. As an example, there are 250 steps along the width of the simulated sample. The following relation is thus used:

$$X = ALEA \times 250$$

where ALEA is randomly chosen between 0 and 1 by Excel. X is the number of the step corresponding to the center of the pit. An equivalent relation is used along the length.

Due to the random aspect of the positioning of the pits, impacts will overlap. In Section 3, we'll see how this problem is treated. It is worth noting that the depth resulting from the overlapping of two impacts is inferior to the sum of the depths that each impact would have generated if the impacts had been isolated.

2.2.2. "Constant power" hypothesis

In order to study the influence of test duration on the evaluation of the volume damage rate V_d, we use the "constant power" hypothesis in two different ways depending on two different phases.

a) The first phase corresponds to the "initialization". During this phase, the experimental results of a test are directly used. Pits are simulated, following the distribution given by the measured histogram (Figure 5). When indentations overlap, an overlapping model is used (see Section 3), and the volume generated then is inferior to the one that would have been obtained if the material had not been strengthened by work-hardening. At the end of the simulation of each impact, two global volumes are calculated: the total volume simulated without overlapping of the impacts ΣV_e, and the total volume resulting from the overlapping of the impacts on the simulated sample ΣV_m. The simulation goes on until the simulated volume damage rate $V_m^d = \frac{\Sigma V_m}{\Delta S \cdot T_1}$ equals the volume damage rate Vd obtained from experimental measurement. The precision between V_m^d and Vd is 1% . Then, from simulations, one can evaluate the volume damage rate without overlapping $V_e^d = \frac{\Sigma V_e}{\Delta S \cdot T_1}$. Plenty initializations can be done in order to get a mean value and a standard deviation on V_e^d. This phase of initialization allows to evaluate the "energy" $\Sigma V_e(T_1)$ that impacted the sample during the test of time exposure T_1 in order to lead to the damaged volume $\Sigma V_m(T_1)$.

b) The second phase corresponds to "predictions", that rely on the relation $\Sigma V_e(T_2) = \frac{T_2}{T_1} \Sigma V_e(T_1)$ established by the "constant power" hypothesis. The aim is to predict the damage of a material for every test duration T_2 from a single test that lasted T_1. Consequently, the same histogram is used for predictions than during the initialization. The principle of the simulation is the same than above, except that the stop criterion now concerns the "energy" $\Sigma V_e(T_2)$. This volume is calculated with a 1% precision. At the end of the simulation corresponding to a T_2 exposure time, a measurable volume $\Sigma V_m(T_2)$ is obtained, leading to an evaluation of the volume damage rate V_m^d for a T_2 test duration.

We will now see the applied overlapping models.

3. OVERLAPPING MODELS

The two overlapping models presented below are mono-dimensional.

3.1. An "all or nothing" model

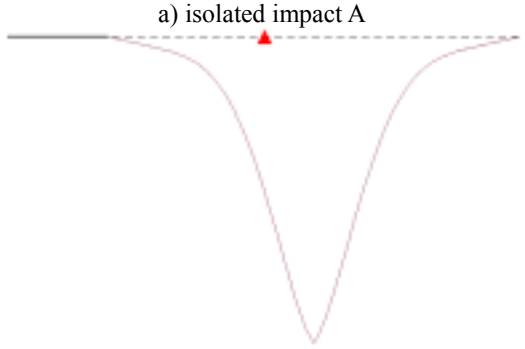
This first model is a simplistic approach of the behavior of a material submitted to overlapped impacts. This model is applied locally on a point that as already been impacted by a pressure wave, leading to a depth h_a under the initial surface. We simulate a new pit supposed to be isolated. Consequently, all the local depths of the new pit are calculated under the initial surface of the sample. When two impacts overlap, two depths are taken into account on each point: the initial depth h_a, and the depth h_b that would have resulted from the new impact if the surface had been virgin. Both depths are thus evaluated under the initial surface of the sample. The "all or nothing" model deals with this situation as follows:

- if $h_a > h_b$, the first energy that impacted this point was bigger than the second. Consequently, we suppose that the local work-hardening was too big for the second impact to damage the sample. Thus, the efficiency of the first impact is supposed to be 100%, whereas the efficiency of the second impact is supposed to be 0%, and the local depth resulting from the overlapping of the impacts remains h_a ;
- if $h_b > h_a$, the second energy that impacted this point was bigger than the first. Consequently, we suppose that the work-hardening

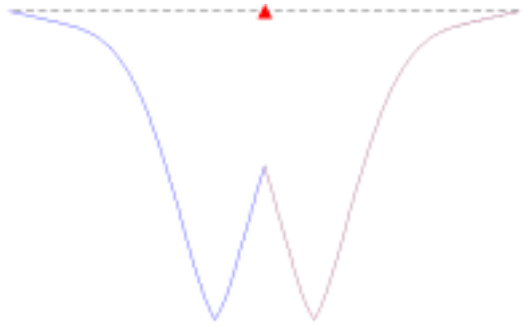
was negligible, and thus the efficiency of the second impact is supposed to be 100%. Moreover, the initial depth h_a is supposed small enough to be considered nil, which means that the efficiency of the first impact is supposed to be 0%. As a result, the final depth resulting from the overlapping of the two impacts is h_b.

This model consists in keeping the biggest of the two depths (under the initial surface) that should overlap at a point of the sample (Figure 6).

a) isolated impact A



b) isolated impact B



c) overlapping of A and B

Figure 6: When two impacts simulated from the initial surface of the sample overlap (figures above and in the middle; the triangle corresponds to the same point of the simulated sample, the different indentations being supposed isolated before overlapping), the deepest points are kept (according to the "all or nothing" model).

3.2. A work-hardening model

To improve the simple model presented above, an other approach has been developed based on a model proposed by [22] and [23]. We adapted it in order to make it usable by our procedure, and restricted it to the incubation period (no mass loss is viewed).

Two relations are required to describe the mechanical behavior of the material. The first one is its strain-stress relation $\sigma = \sigma_e + K\varepsilon^n$ (Figure 7 above), where σ is the stress, ε the strain, σ_e the elastic stress, n the work-hardening coefficient, and K a parameter characteristic of the material. This relation is valid for $\sigma < \sigma_r$ (σ_r is the rupture stress) and $\varepsilon < \varepsilon_r$ (ε_r is the rupture strain), which is considered in the present study.

The second relation required is the work-hardening profile of the material. Indeed, when a material is subjected to plastic strains, it keeps residual strains along a depth "l" after unloading. For a material work-hardened without mass loss, this profile is represented by the relation $\varepsilon(x) = \varepsilon_s\left(1 - \frac{x}{l}\right)^{\theta}$ (Figure 7 below) where $\varepsilon(x)$ is the residual strain at a depth x under the initial surface, ε_s is the surface residual strain, l is the work-hardened depth, and θ is a shape parameter.

This model has been applied in order to lead an energy approach of the overlapping of impacts, which would allow us to calculate the depth resulting from two impacts overlapping at the same point. First, we had to link energy and depth. Let's consider a unit surface area of the sample. From its virgin state (that means before being impacted by pressure waves), this "point" is impacted by a single pressure wave. The surface strain resulting from this impact is locally called ε_i (ε_i has the same signification as ε_s), and remains inferior to ε_r. The work-hardened depth is called l_i, and the local depth resulting from the damaging of the material is h_i. The volume plastic energy absorbed by every layer under the impacted point is $\int_0^{\varepsilon} \sigma d\varepsilon$. The total plastic energy $W_i = \int_0^{l_i}\left[\int_0^{\varepsilon} \sigma d\varepsilon\right]dx$ absorbed by the unit surface area can be calculated thanks to the work-hardening profile and the stress-strain relation. It can be shown [24] that the energy W_i is related to the depth h_i by the relation:

$W_i = \sigma_e h_i + \frac{B}{A} h_i^A$, where A and B are constant for a given material and depend on mechanical parameters of the materials:

$$\begin{cases} A = \dfrac{n\theta + \theta + 1}{\theta + 1} \\ B = \dfrac{K\varepsilon_r^{\frac{n}{\theta+1}}}{n+1}\left(\dfrac{\theta+1}{L}\right)^{\frac{n\theta}{\theta+1}} \end{cases}$$

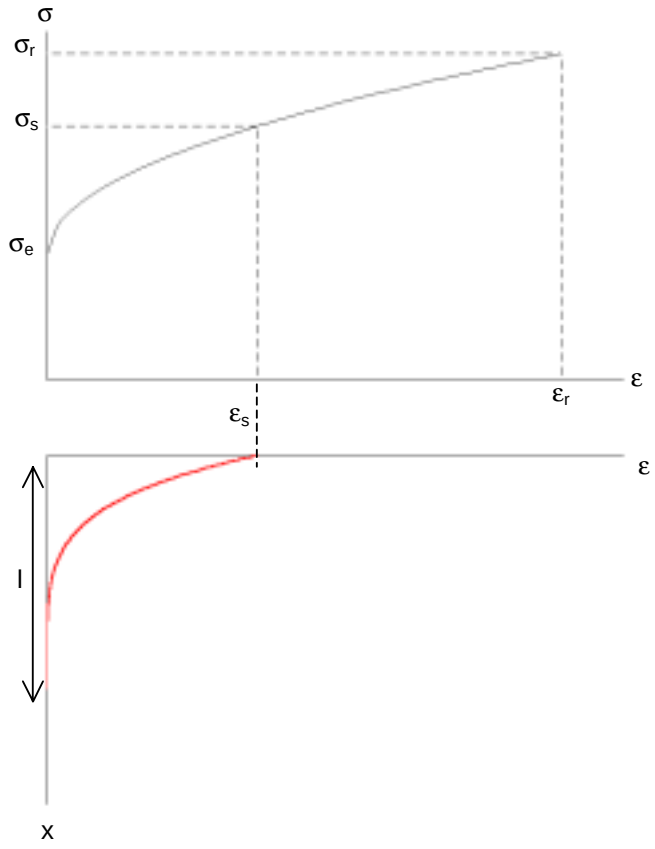


Figure 7: For a given material, the work-hardened length "l" depends on the residual surface strain ε_s, The residual stress and strain can be calculated for every layer under the impacted point thanks to the work-hardening profile (below) and the stress-strain relation (above).

The only new parameter is L: it is the length of the work-hardened zone for a total work-hardening of the material, i.e. when the residual surface strain is ε_r.

From these considerations, we have to define three depths related to the same point (or unit surface area) of the sample, and measured from the initial surface of the sample:

- the initial depth h_1 : this is the depth before the new pit overlapping
- the impact depth h_i : this is the depth that should result from the new pit if the surface was virgin
- the final depth h_2 : this is the depth resulting from the overlapping of h_1 and h_i thanks to this model.

One notes that this study only tackles the work-hardening topic (no mass loss is viewed): consequently, these three depths correspond to situations in which they can be related to a total plastic energy absorbed by a unit surface area by the above relation:

$$W = \sigma_e h + \frac{B}{A} h^A$$

If we suppose that there is no energy loss, the final energy that has been absorbed by the unit surface area is $W_2 = W_1 + W_i$, which leads to a relation between h_1, h_i and h_2:

$$\sigma_e h_2 + \frac{B}{A} h_2^A = \sigma_e (h_1 + h_i) + \frac{B}{A}\left(h_1^A + h_i^A\right)$$

The final depth h_2 calculated from this implicit equation is such that:

$$h_2 > h_1 \; ; \; h_2 > h_i \; ; \; h_2 < h_1 + h_i$$

This work-hardening model has more physical meaning than the "all or nothing" model, but it is more difficult to use because of the unknown parameters L and θ. According to [23], for stainless steel, L = 200µm, θ = 5, n=0.5, K=900 MPa. Further experimental results from mechanical and metallurgic tests are required to characterize other materials.

4. SOME RESULTS

To illustrate the proposed procedure, a few tests have been done with the "all or nothing" model implemented in the calculation code. They were based on an experimental study carried out in the MODULAB test rig of EDF-R&D [1,5].

a) Influence of time exposure:

In the first application example, simulations were performed in order to rectify the influence of the exposure time on the volume damage rate. The study concerned three aluminum samples exposed to a water cavitating flow with a reference flow velocity v=32m/s and three different exposure times T=10, 20, and 30s (Figures 9).

At first, an "initialization" phase of the sample 1 (T=10s) was performed. Based on the experimental pit histogram given in Figure 5, we simulate the solid surface damage in order to obtain V^d_m=Vd=8030 $\mu m^3/mm^2/s$ (i.e., the measurable volume damage simulated by the code is equal to the volume measured by experimental tests). To simulate this volume damage, an "effective energy" (correlated to V^de) needs to be applied on the solid material and is evaluated. Indeed, the parameter V^de characterizes the aggressiveness of the cavitating flow. From this calculated rate, the code is able to predict the volume damage that would be observed on a given material surface exposed to the same cavitating flow during every time T.

For the given example, the code evaluates V^de=8300 $\mu m^3/mm^2/s$. The application of this "energetic" rate during 20s leads to a V^dm=8050 $\mu m^3/mm^2/s$ (to be compared to experimental results Vd=7900 $\mu m^3/mm^2/s$). The application during 30s leads to V^dm=7360 $\mu m^3/mm^2/s$ (to be compared to experimental results Vd=6370 $\mu m^3/mm^2/s$). The maximum difference between prediction and experiment is 16%.

It is worth noting that:

- V^de is bigger than V^dm because of the existence of overlapped impacts. For large test durations, the number of overlapped impacts increases and the value of V^dm (and Vd) can be strongly influenced by T. Therefore, the measured volume damage Vd cannot be related directly to the cavitating aggressiveness. A reliable analysis and evaluation of the cavitating flow erosion power needs to be based on V^de values.
- when the sample surface is too much damaged (generally for large exposure times, as illustrated in figures 9), the automatic measurement of the damage is not reliable and Vd is generally under evaluated [1]. The discrepancies found between

$V^d m$ and Vd presented above can be attributed also to this measurement effect.

- hence, to do a reliable simulation, the experimental histograms of pit distribution considered in the phase of "initialization" needs to be deduced from tests with small exposure times (about 10s).

b) Material transposition:

From the 10s initialization on an aluminum sample presented above (i.e., $V^d e$=8300 $\mu m^3/mm^2/s$ for the considered cavitating flow and for aluminum) and the corresponding pits histogram, we tried a material similarity test with a copper sample exposed to the same cavitating flow for 60s.

Based on transposition laws proposed in [2], the "effective energetic" rate $V^d e$ for the copper can be deduced from:

$$V_e^d\,(copper) = \frac{\beta_{aluminum}}{\beta_{copper}} V_e^d\,(aluminum)$$

where $\beta_{aluminum}$=4 J/mm^3 and β_{copper}=20 J/mm^3 are mechanical properties of the materials, given by [2].

The damage volume rate predicted by the code (from the value $V^d e_{(copper)}$=1660 $\mu m^3/mm^2/s$) for the copper sample is $V^d m$ = 1350µm3/mm2/s, which has to be compared to the measured volume damage rate Vd=1180µm3/mm2/s. The prediction is only 16% upper the measure, which is reasonable considering both the simplicity of the "all or nothing" model and the long exposure time (60s) of the copper sample, leading to the underestimation of Vd.

c) Flow velocity effect:

Other tests have been done in order to see whether a correlation would appear between the speed of the flow and the energetic volume rate $V^d e$. The results, displayed on Figure 10, allow us to estimate a first tendency for the velocity influence. It can be seen that the energetic volume rate rises approximately as $V^d e \sim v^5$. Nevertheless, further experimental works are necessary to verify and improve these results.

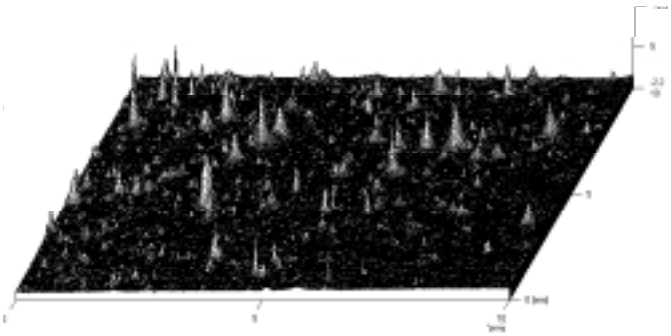


Figure 9a: visualization of the surface of an aluminum sample exposed to a cavitating flow during T=10s (water flow velocity=32m/s). The volume damage rate measured by experimental analysis is Vd= 8030 $\mu m^3/mm^2/s$.

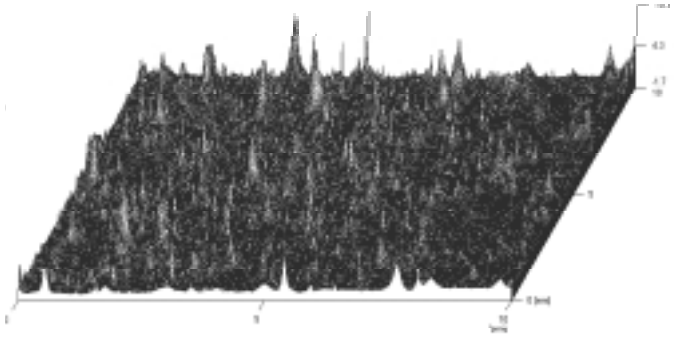


Figure 9b: visualization of the surface of an aluminum sample exposed to the same cavitating flow during T=30s. The volume damage rate measured by experimental analysis is Vd=6370 $\mu m^3/mm^2/s$.

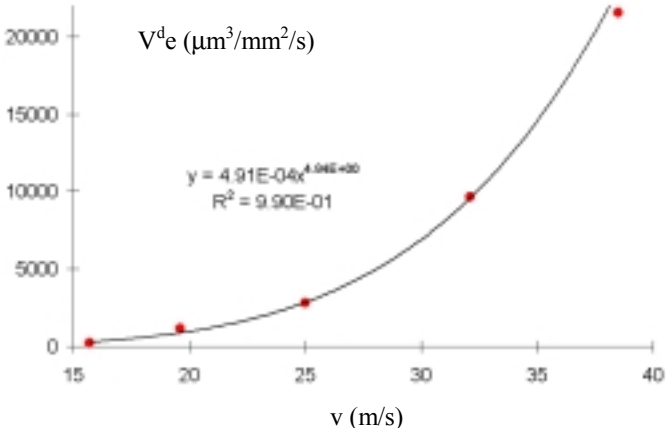


Figure 10: Influence of flow velocity on the effective energetic volume rate $V^d e$ evaluated on aluminum samples for different flow velocities.

5.IMPROVEMENTS AND PROSPECTS

To analyze material samples damaged by cavitating flows and then evaluate flow aggressiveness, an experimental and numerical methodology has been developed based on 3D profilometry measurements. During these works, we have pointed out the strong influence of analysis parameters and proposed some corrections to obtain a reliable estimation of volume damage rates.

The aim of the present study was to develop a procedure to evaluate and rectify the influence of the test duration on damage rates results obtained during incubation period of cavitation erosion. In this way, a calculation code was performed which simulates, according to a given pit distribution, cavitation impacts on the solid samples and predicts material damage.

To take into account the phenomena of work-hardening and the impacts overlapping, two mono dimensional theoretical models were implemented in the code: an "all or nothing" model and a quasi-static one. This second model will be extended to

simulate also the mass loss phenomenon associated to cavitation erosion.

Moreover, concerning work-hardening and mass loss model, we consider implementing also a two dimensional approach which takes into account dynamic aspects of material behavior [17].

A first application example of the “all or nothing” model was given in this paper in order to illustrate the procedure. As a matter of fact, a more detailed validation of the methodology needs more experimental results concerning cavitation mark tests, metallurgical and dynamic solid characterization.

New experimental tests are planned in the framework of the European Research Program PREVERO *(PREVentive reduction of diesel engine emulsion caused by cavitation EROsion)*, and in collaborations with EDF-R&D in order to support and improve the present procedure.

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