Impact Load Measurements in an Erosive Cavitating Flow

Impact load measurements were carried out in a high-speed cavitation loop by means of a conventional pressure sensor flush-mounted in the region of closure of the cavity where maximum damage was observed. The sensor was dynamically calibrated by the ball drop test technique. Pressure pulse amplitudes were measured at different velocities and constant cavitation number and cavity length. It was found that pressure pulse height spectra follow a simple exponential law, which depends upon two parameters interpreted as a reference peak rate and a reference load. By exploring the dependence of both parameters on flow velocity, it was possible to show that the various histograms measured at different velocities can be reduced to a unique non-dimensional one and derive scaling laws, which enable to transpose results from one velocity to another. The measured values of impact loads are compared to similar data in the literature, and the impact load spectra are discussed with respect to pitting test results available from a previous investigation. It is concluded that an uncertainty remains on the measured values of impact loads and that a special effort should be made to compare quantitatively pitting test results and impact load measurements. To evaluate the coherence of both sets of data with each other, it is suggested to introduce two-dimensional histograms of impact loads by considering the size of the impacted area in addition to the measured impact load amplitude. It is conjectured that the combination of impact load measurements and pitting test measurements should allow the determination of such two-dimensional histograms, which are an essential input for analyzing the material response and computing the progression of erosion with exposure time. [DOI: 10.1115/1.4005342]

1 Introduction

The concept of an impact load of high intensity and short duration generated locally on a wall by a collapsing cavitation bubble is a key issue in cavitation erosion. It is the basic component of the so-called cavitation intensity [1], which aims at characterizing the hydrodynamic aggressiveness of a cavitating flow. Since cavitation erosion is actually the result of the material response to repeated impact loads, it appears fundamental to accurately determine impact loads in order to be able to predict the erosion damage.

In 1979, Hammitt [2] proposed to measure the individual pressure pulses due to bubble collapses and introduced pressure pulse height spectra to characterize a cavitating flow. He proposed to evaluate the acoustic energy emitted by any cavitation bubble collapse using linear acoustic theory in which the energy flux \( E \) radiated by a pressure wave \( p \) is given by the time integral \( E = \int p^2 dt \) (\( c \) is the acoustic impedance of the liquid). De and Hammitt [3] defined the cavitation acoustic power as the summation of the previous energy fluxes for all the identified pulses and found, in the case of a Venturi flow, a linear correlation between the cavitation acoustic power and the cavitation damage rate in terms of mean depth of penetration rate (MDPR) (see also Ref. [4]).

Following these pioneering works, which demonstrated the interest of pressure pulse height measurements for cavitation erosion studies, several researchers tried to measure as accurately as possible pressure pulses in various types of cavitating flows. Such measurements are particularly difficult because of the extreme features of the pressure pulses, which are of very short duration (typically a few microseconds) and cover a small surface area (typically a few tens or hundreds of micrometers only). If a conventional pressure sensor is used for measurement, the mechanical resistance of the sensor to cavitation impacts is also an important issue.

Okada et al. [5] and Hattori et al. [6] developed a pressure detector able to measure impact loads and erosion damage simultaneously. From the measurement of the maximum amplitude \( p \) of the various pressure pulses, they computed what they call the accumulated impact energy \( \sum p^2 \) and found a linear correlation between the volume loss and the impact energy. An important conclusion they obtained states that this correlation depends upon the material but is independent of the type of apparatus (Venturi or vibratory system) and of the test conditions. More recently, Hattori et al. [7] proposed an evolution of this method applied to the prediction of the incubation period and based on a fatigue failure approach.

Momma and Lichtarowicz [8] developed pressure sensors using piezoelectric polyvinylidene fluoride (PVDF) films to measure impact loads in a cavitating jet apparatus. PVDF transducers are capable of enduring severe cavitation erosion and have a high natural frequency favorable to the capture of short duration pulses. By using transducers of various sizes, they showed that, as the transducer area is increased, the signal height becomes independent of the area and concluded that the transducer should not be too small. They used both a pencil lead breaking technique and a dropping ball technique to calibrate their transducers dynamically. As also shown by Soyama et al. [9], the lead breaking technique leads to short pulses whose duration is comparable to those observed in cavitating flows. Let us mention that magnesium oxide single crystals have also been used to evaluate impact loads from the observation of dislocation etch pit patterns [10].

The work presented here follows the same objective of measuring impact load spectra in a cavitating flow. The experimental facility and the measuring procedure are described in Sec. 2. Impact load spectra at different velocities are presented in Sec. 3 from which scaling laws with flow velocity were derived. The obtained values of impact loads are compared to other results in the literature, and a qualitative comparison between pulse rate and pitting rate is presented in Sec. 4.
2 Experimental Facility

2.1 Cavitation Erosion Facility. The tests were conducted in a cavitation loop with a maximum operating pressure of 40 bars. The facility is presented in more details in Ref. [11]. The test section is shown in Fig. 1. The inlet flow is axial and goes through a nozzle of 16 mm diameter. The outlet flow is radial and goes in between the two flat surfaces defined by the nozzle and the sample to be eroded, which is facing the nozzle exit at a distance of 2.5 mm. In Fig. 1, a Perspex window was used instead of the sample for visualization purposes. The upstream pressure $p_u$ was varied between 10 bars and 40 bars. The velocity on the cavity $V_c \approx \sqrt{2(p_u - p_l)/\rho}$ (where $\rho$ is the density, $p_v$ vapor pressure) could vary between 45 m/s and 90 m/s. The influence of gas content was not investigated in the present study. However, pressurization is made using a vessel of small section, which limits the surface of contact of nitrogen (used for pressurization) with water. It is then expected that dissolution of nitrogen into water is limited and that the gas content is almost independent of the pressurization level.

Cavitation has the form of an annular cavity attached to the nozzle exit. The cavity is the white area visible in Fig. 1. Maximum erosion is observed in the closure region of the cavity. The length of the cavity is controlled by the value of the cavitation number defined by $\sigma = (p_d - p_l)/(p_u - p_d)$ where $p_d$ is the pressure in the downstream duct. For all tests, the cavitation number was kept constant so that the cavity length was constant too. The value chosen for the $\sigma$ parameter is 0.9. This value ensures the cavitation erosion to take place in the central part of the sample, which is convenient for analysis.

2.2 Sensor. The pulses due to the collapse of cavitation bubbles have been measured by means of a commercial piezoelectric pressure sensor (PCB 108A02). The sensor is flush-mounted on the sample in the vicinity of the cavity end (see Fig. 2). The manufacturer specifies a natural frequency larger than 250 kHz and a rise time smaller than 2 $\mu$s. The outer diameter of the transducer is 6.2 mm. The sensitive surface is the most inner part visible in Fig. 3 whose diameter is 3.6 mm.

The transducer surface, which was exposed to cavitation, has been damaged as shown in Fig. 3. In order to check that the response of the transducer was not significantly affected by the pitting of its membrane, a reference pulse height spectrum was measured at the beginning and at the end of the test campaign. Figure 4 shows that the two spectra are satisfactorily superposed so that it was concluded that pitting of the transducer sensitive surface did not change significantly the transducer response. It should be observed that the experimental procedure was optimized in order to minimize as much as possible the duration of exposure of the transducer to cavitation. The cumulative exposure time for the whole campaign was of the order of a few minutes only so that the damage remained superficial and did not affect the stiffness of the membrane.

The transducer was calibrated using the ball drop test technique. A stainless steel ball of radius 1.8 mm and mass $m = 0.44g$ was dropped on the transducer from a given height $h_1$. The rebound height $h_2$ was measured, and it was estimated from several tests that $h_2 \approx 0.64h_1$. The incident velocity just before contact $v_1 = \sqrt{2gh_1}$ ($g$ gravity acceleration), and the rebound velocity just after contact is given by a similar equation $v_2 = \sqrt{2gh_2}$.

The load applied to the transducer is a function of time and changes during contact of the ball with the transducer. The detailed time evolution of the load and in particular the maximum load cannot be predicted from simple mechanical considerations. Therefore, the calibration was not based on the maximum value but on the time average value of the load during the shock, which can easily be computed from a momentum balance,

$$F = \frac{m(V_1 + V_2)}{\tau}$$

where $\tau$ is the shock duration that was determined from the recorded transducer signal.

Typical signals delivered by the transducer during calibration are presented in Fig. 5 for $h_1 = 0.5$ m. A good reproducibility of the ball drop test is observed. The average amplitude $A$ (in Volt) was determined by the integration of the signal with respect to time. In this case, the shock duration was $\tau \approx 14$ $\mu$s and the mean load deduced from Eq. (1) was $F \approx 176V$. The sensitivity of the transducer (in V/N) was computed from the ratio $A/F$. Note that the ratio of the mean amplitude to the maximum amplitude was found to be 0.59 by integration of the signal. This value is an indicator of the shape of the loading and unloading curve. A triangular signal would give 0.5 and an arch of sinusoid $2/\pi \approx 0.64$.

The ball drop test technique leads to an average sensitivity of 7.3 mV/N based on several calibration tests with an uncertainty of $\pm 4.5\%$. This force calibration was compared to the pressure calibration given by the manufacturer, in this case 74.05 mV/MPa. Assuming that the pressure is applied uniformly to the 3.6 mm diameter sensitive surface, pressure sensitivity can easily be converted into force sensitivity. The force sensitivity deduced from the manufacturer’s calibration is 7.27 mV/N, which is in pretty good agreement with the value obtained from the ball drop test technique.

All measurements below are presented in load unit (N). This is because the surface of the loaded area due to a collapsing cavitation bubble is much smaller than the sensitive surface of the transducer. Then, the transducer is far from being uniformly loaded and the signal can be interpreted only in terms of load and not of

![Fig. 1 View of the cavitating test section. The white region attached to the nozzle exit is a ring type cavity.](image-url)
pressure. The impact pressure could be estimated only if the impacted surface area is known, which is not the case here.

2.3 Signal Acquisition and Processing. The signal delivered by the sensor was recorded using a digitizer with 8-bit resolution and 50 MHz bandwidth. For the determination of impact load spectra, 60 s of signal was acquired at a sampling rate of 2 MSamples/s. Additional acquisitions at a higher sampling rate of 50 MSamples/s were made in order to investigate in more details the shape of the impact load pulses (cf. Sec. 4.1).

Signal analysis consisted in the detection of pulses and the measurement of their height. A minimum threshold, in this case 0.8 V, was considered for pulse detection. This value was chosen in comparison with pitting tests conducted separately [12]. It is such that the pulse rate (per unit time and unit surface area) is roughly comparable to the pitting rate on a soft material such as aluminum. The underlying idea is to measure only those pulses that are most likely responsible for pitting and ignore the smallest amplitudes, which are not expected to make any damage on the softest materials. It should be observed that the chosen value of 0.8 V is much higher than the background noise. A comparison of pulse rate and pitting rate is available in Sec. 4.2.

As explained in Sec. 4.1, the main pulse is generally followed by secondary pulses of decreasing amplitude due to transducer ringing. In order to detect only the main pulse, a locking time of 10 μs was chosen after a peak detection during which the detection procedure is hold on. This locking time combined with the amplitude threshold allowed us to avoid multiple counting for a single hydrodynamic impact.

3 Results

Impact load measurements have been conducted for different operating conditions in order to investigate the effect of flow velocity on cavitation intensity. Even though the flow velocity was changed, the cavitation number was kept constant so that the cavitation length was also constant and the cavitating flows were geometrically similar.

Typical time signals are presented in Fig. 6 where two major effects are visible. Firstly, the frequency of pulses increases with flow velocity, which is likely connected to an increase in bubble production rate. Secondly, the amplitude of pulses also increases which indicates an increase in the strength of bubble collapses with flow velocity. Both effects concur to the increase of cavitation intensity, which is far from being linear as shown below.
Time signals were also processed in order to derive the impact load spectra at different upstream pressures or flow velocities. The results are presented in Fig. 7 in the form of cumulative histograms of impact loads as a function of amplitude. The lower horizontal axis gives the amplitude in volts whereas the upper horizontal axis gives the amplitude in newtons using the calibration results.

It appears that all spectra \( N(F) \) (where \( N \) is the cumulative peak rate per unit surface area and \( F \) the load in N) follow pretty well an exponential law of the type

\[
\dot{N} = \dot{N}_0 e^{F/F_0} \quad (2)
\]

This law depends upon two constants \( \dot{N}_0 \) and \( F_0 \), which can be considered as the reference peak rate and the reference load.

It was qualitatively observed in Fig. 6 that both the rate and the amplitude of peaks increase as flow velocity increases. The previous decomposition (Eq. (2)) makes it possible to separate both effects and quantitatively estimate the influence of flow velocity on peak rate and peak amplitude separately. This is achieved via the analysis of the dependence of each of the two constants \( \dot{N}_0 \) and \( F_0 \) upon flow velocity. Figure 8 shows the evolution of both parameters with flow velocity \( V \). The load \( F_0 \) only slightly increases like \( V^{0.64} \) whereas the peak rate \( \dot{N}_0 \) increases much more rapidly like \( V^{2.9} \). As a comparison, let us recall that the classical water-hammer model would predict a linear evolution of the impact pressure with the velocity of the microjet impacting the wall. Note that it is not straightforward to deduce from these two exponents (2.9 and 0.64) the exponent of the power law for peak rate versus flow velocity. Typical values are given in the caption of Fig. 11. They depend upon the load threshold and vary between 4.5 and 9.6 for the present investigation.

As a result, scaling laws followed by impact load spectra can be derived. According to the previous power laws and in order to remove the dependency on flow velocity, ratios \( N/V^{2.9} \) and \( F/V^{0.64} \) are considered. They are made non-dimensional by considering the reference peak rate \( \dot{N}_0 \) and the reference load \( F_0 \) (Eq. (2)) at \( V_0 = 44.6 \) m/s. In other words, the non-dimensional peak rate...
at a velocity \( V \) is defined by \( \left( \frac{F}{N_0} \right) \times \left( \frac{V}{V_0} \right)^{2.9} \) and the non-dimensional load by \( \left( \frac{F}{N_0} \right) \times \left( \frac{V}{V_0} \right)^{0.64} \). Using these new variables, the impact load spectra of Fig. 7 have been re-plotted in a non-dimensional way on Fig. 9. All the spectra arrange around an almost unique non-dimensional spectrum. This proves that, in the present domain of investigation, an impact load spectrum measured at a given velocity can be successfully transposed to another velocity assuming that loads vary like \( V^{0.64} \) and frequencies like \( V^{2.9} \).

4 Discussion

4.1 Impact Load Amplitude. As mentioned in Sec. 2.3, additional acquisitions at a higher sampling rate of 50 MSamples/s were performed in order to investigate the detailed shape of the pulses. Figure 10(a) presents a typical pulse. Whatever may be the operating conditions and the pulse amplitude, the main pulse is always followed by secondary pulses of smaller amplitude.

A frequency analysis (Fig. 10(b)) points out a frequency content around 250–300 kHz, which corresponds to the resonant frequency of the transducer. Hence, it is likely that the secondary pulses are not connected to the cavitation phenomenon but due to the resonance of the transducer. The sensor is probably not optimal for such measurements, and its natural frequency is most likely too low in comparison to the frequency content of the impact load.

It is not yet clear to which extent the amplitudes measured here could be affected by this phenomenon of transducer ringing. If the sensor is modeled as a simple damped second order oscillator, it can be expected that, when the characteristic frequency of the impact increases and approaches the natural frequency of the transducer, the measured amplitude would be overestimated due to resonance. On the other hand, if the characteristic frequency of the impact load largely exceeds the sensor’s natural frequency, the transducer cannot follow accurately the pressure rise and the maximum amplitude would be underestimated. To remove this uncertainty on the measured amplitudes, it would be helpful to use another type of sensor of higher natural frequency as a PVDF sensor for instance.

According to the data presented in Fig. 7, the measured amplitudes lie in the range 100–500 N. These values appear to be comparable to other measurements available in the literature. Soyama et al. [9] using PVDF transducers measured impact loads up to 200 N in a cavitating jet apparatus for a jet velocity at the nozzle outlet in the range 126–155 m/s. Franc and Michel [13] report measurements with various transducers in a cavitating vortex apparatus up to 300 N.

On the other hand, Carnelli et al. [14] estimated the impact loads from joint pitting and nanoindentation tests and found maximum values much smaller of the order of 20 N for the same experimental device as the one used here. Hattori et al. [15] measured impact loads in a cavitating liquid jet test chamber (ASTM G134-95 standard) at flow velocities up to 184 m/s and obtained a maximum value of 20 N, too.

Furthermore, it can be observed that the largest pits obtained on the aluminum alloy Al 7075 in the present facility are close to 200 \( \mu \)m in diameter [12]. If the largest pits are associated to the highest loads (500 N), the corresponding stress would be of the order of 16 GPa. In the case of a submerged cavitating liquid jet, Momma and Lichtarowicz [8] found that the loading pressure increases significantly as the pit size decreases and varies between about 2 GPa for large pits of 200 \( \mu \)m to 300 GPa for small pits of 10 \( \mu \)m.

This discussion shows that there is a significant discrepancy between estimates of impact loads obtained by different
techniques even for the same cavitating flow and that further investigations are needed to reconcile the impact load data. Comparison between impact load measurements and pitting test results could be helpful for that.

### 4.2 Comparison of Peak Rate and Pitting Rate

Since pitting test results are also available for the same facility from a previous investigation [12], the evolution with flow velocity of the peak rate can be compared to that of the pitting rate. Figure 11(a) presents a comparison of the peak rate with the pitting rate on an aluminum alloy Al 7075 whereas Fig. 11(b) presents a comparison of the same peak rate data with pitting tests on a nickel aluminum bronze alloy (cf. Ref. [12] for more information on the materials).

Peak rate depends upon the load threshold while pitting rate depends upon the pit diameter threshold. Since there is no simple equivalence between impact load and pit diameter, the comparison between peak rate and pitting rate is not straightforward and several values of load threshold (for peak data) and diameter threshold (for pit data) have been considered in Fig. 11 for discussion.

From a qualitative viewpoint, it appears that peak rates and pitting rates are comparable in orders of magnitude. As a matter of fact, there is a large spectrum of impact loads in a cavitating flow with a very broad range of amplitudes. Those of small amplitude are very numerous and are due to weak collapses, which are not expected to cause any pit. For cavitation erosion investigations, it is then important to set the minimum value of the load threshold for peak detection at a high enough level so that the peak rate remains comparable to the pitting rate. As mentioned in Sec. 2.3, this condition was used as a guideline to choose the minimum value of the threshold. When fulfilled as it is the case here, it can reasonably be assumed that the investigation will be focused on the most energetic collapses, which are actually able to produce an indentation on the materials of interest.

In addition, Fig. 11 shows that peak rate and pitting rate both increase very significantly with flow velocity. This result remains qualitative since there is no obvious correlation between the two exponents of the power laws, which describe best the evolution of pitting rate and peak rate with flow velocity and which are given in the figure captions. From Fig. 11, peak rate appears to increase generally more rapidly with flow velocity than pitting rate.

A more quantitative discussion would require a better description of the impact due to the collapse of a cavitation bubble. In the present paper, a collapse is characterized by a single parameter, namely the impact load generated on the wall. At least, one important parameter is missing in the analysis, which is the size of the impacted area. This parameter is out of reach of the present investigation based on the use of a sensor whose sensitive surface is much larger than the impacted area and which is unable to discriminate impacts of equal load but different size.

To better describe the aggressiveness of a cavitating flow, impacts should be classified by both load $F$ and size $D_i$. Two-dimensional histograms should then be introduced to characterize the cavitation intensity instead of the one-dimensional histograms used here (Fig. 7). Such a two-dimensional histogram is obviously not easy or even possible to measure directly. However, it can be conjectured that it would be possible to reconstruct it by bringing together impact load measurements and pitting tests. Roughly speaking, information on amplitude would be extracted from...
on the other hand, histograms of impact loads measured in the present work can also be derived from two-dimensional histograms by simply integrating the distribution with respect to the variable \( D_i \), since the impact load measuring technique actually integrates all \( D_i \)-values. As a consequence, both histograms of peak rate and pitting rate can be derived from a unique two-dimensional basic histogram considered here as a measure of the cavitation intensity.

It would be most helpful to investigate the inverse problem of determining the cavitation intensity (or the two-dimensional histogram) from both impact load measurements and pitting tests. Further investigations are needed to establish the feasibility of this inverse problem and underline the compatibility conditions that impact load measurements and pitting test results should meet. It can be expected that an inverse solution could be found provided the two sets of data, which are strongly interlinked but obtained by fully independent measuring techniques, are actually coherent with each other. This is a perspective of the present work.

5 Conclusion

Impact load measurements are an essential issue in cavitation erosion studies since they define how the material is loaded under the bubble collapses. It can be expected that an accurate knowledge of the characteristics of impact loads (in terms of amplitude, size, rate of loading and unloading, radial distribution, etc.) associated with an appropriate model of material response (see for instance Refs. [11,16]) would enable us to predict numerically the time evolution of damage.

The results presented in this paper are a contribution to impact load measurements. It is shown that simple measurements carried out with a conventional pressure sensor flush mounted in the region of cavitation erosion can easily provide us with valuable information. As an example, the present investigation has shown that the amplitude of impact loads increases moderately with flow velocity \((\propto \sqrt{V_{\text{mean}}})\) whereas the frequency of impact loads increases much more rapidly \((\propto V^{1.9})\). By introducing these trends into a suitable change of variables, it was possible to derive scaling laws with flow velocity and superimpose all measured spectra on a unique non-dimensional spectrum.

Although relative comparisons of impact load spectra appear quite satisfactory, the absolute values of impact loads still remain to be confirmed. In particular, it turned out that the present measurements do not corroborate the values of impact loads derived from an analysis of pitting tests using conventional nanoindentation tests at small strain rate [14]. Further investigations are then needed to consolidate the measured values of impact loads.

This work also presents a tentative comparison of peak rates and pitting rates. Both are comparable in orders of magnitude and exhibit a rapid increase with the flow velocity. However, a more in-depth comparison is difficult to achieve. In particular, it appears that it is difficult to check the mutual consistency of impact load measurements and pitting test results. Our analysis tends to prove that the amplitude of impact loads is probably not enough alone to interpret the results and that it would be necessary to introduce the size of the impacted area as an additional parameter and make the histograms of impact loads become two-dimensional. It is expected that the combination of impact load measurements and pitting test results would enable the derivation of such two-dimensional histograms, which are not directly measurable but which are considered as a promising estimate of the so-called cavitation intensity.

Acknowledgment

This research was conducted under a NICOP project funded by the Office of Naval Research. The authors wish to thank Dr. Ki-Han Kim from the Office of Naval Research (ONR) and Dr. Richard Vogelsong from the Office of Naval Research Global (ONRG) who supported this work. They are also very grateful to

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Dr. Farrel Martin (Naval Research Laboratory) and Dr. Martin Donnelly (NSWCCD) for many fruitful discussions and to Ariane Greco for her contribution to the measurements.

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