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CORRELATION BETWEEN COLLAPSE PRESSURE AND MATERIAL LOSS IN CAVITATIO EROSION

M.E. Marcio Gustavo Di Vernieri Cuppari
Laboratório de Fenômenos de Superfície, Departamento de Engenharia Mecânica, Escola Politécnica da Universidade de São Paulo, Av. Prof. Mello Moraes 2231, 05508-900, São Paulo SP

Dr. Linilson Rodrigues Padovese
Laboratório de Fenômenos de Superfície, Departamento de Engenharia Mecânica, Escola Politécnica da Universidade de São Paulo Av. Prof. Mello Moraes 2231, CEP 05508-900, São Paulo SP

Eng. Alex Fabiano Oraggio
Laboratório de Fenômenos de Superfície, Departamento de Engenharia Mecânica, Escola Politécnica da Universidade de São Paulo Av. Prof. Mello Moraes 2231, CEP 05508-900, São Paulo SP

Flávio Onofre Castanho
Laboratório de Fenômenos de Superfície, Departamento de Engenharia Mecânica, Escola Politécnica da Universidade de São Paulo Av. Prof. Mello Moraes 2231, CEP 05508-900, São Paulo SP

***Abstract**: Cavitation occurs in hydraulic machinery due to the repeated growth and collapse of bubbles, which can arise during the flow of a liquid. The stress generated by this collapse is high enough to cause a severe wear in the nearby surfaces. Until today, it is impossible to predict the service life of a component subjected to cavitation. The reason for this lack of predictability is that the mechanisms involved in material loss are not completely understood. During the last years, the interest in the use of sensors to study cavitation erosion has increased. The aim of this paper is to investigate the mechanisms of cavitation erosion by means of a piezoelectric polymer film sensor (PVDF). The sensor was positioned near a cavitation zone created by a vibratory device. Over that sensor was placed an Aluminum plate. This experimental arrangement permitted to acquire data about the behavior of this material during the test. The results showed that there is good correlation between the information from the signal and the mass loss of the sample. Tests were performed at different amplitudes in order to verify the influence of this parameter in the mass loss of the sample.*

***Key words**: Cavitation, PVDF, sensor, signal analysis*

1. INTRODUCTION

Cavitation can be defined as the repeated growth and collapse of small bubbles, which can appear during the flow of a liquid as result of localized pressure drop. This collapse generates very high and transient stresses in vicinity of collapsing regions and if this occur near a solid surface, can cause material damage originating a severe wear process known as cavitation erosion. Hydraulic machinery such as pumps and turbines are subjected to this wear which increases maintenance costs and decreases service life. Until today, it is not possible to predict the conditions for which cavitation erosion will occur or its rate. Although this phenomenon is known for a long time, there is no mathematical model to predict the wear rate of a part subject to cavitation. Lord Rayleigh in 1917 (Rayleigh, 1917) modeled the growth and collapse of a single bubble subject to a variation of pressure. Since then, researchers have addressed his problem with different degrees of complexity (Hunter 1961, Brennen 1995) and these models can predict with reasonable confidence the dynamics of a collapsing bubble. However, the cavitation damage is not due to a collapse of a single bubble, but rather due a collapse of a cluster of bubbles. These clusters can collapse in a way that is much more damaging than the collapse of a single bubble.

For the development of a mathematical model able to predict cavitation erosion, it is necessary to obtain information about the mechanics of cavitation and the behavior of the material as well. For that task, there has been an increasing interest in the use of sensors and signal analysis to study this phenomenon. The use of these techniques can provide information about the pressures developed during the bubble collapse such as magnitude, temporal and spatial distribution. In the recent years the interest piezo films made with PVDF.

The PVDF (Polyvinidelene Fluoride) is a polymer which when subjected to a high polarizing voltage present a strong piezoelectric effect. Sensors made with PVDF presents some important features such as a wide frequency range (0.001 to 10^9 Hz), low acoustic impedance and high voltage output (higher than piezoceramics for the same force imput). The aim of this work is to study the cavitation erosion problem in a vibratory apparatus with the help of PVDF sensors

2. EXPERIMENTAL PROCEDURE

Cavitation was produced in a vibratory device (TELSONIC SG 1000) operated at 20 kHz resonant frequency. The test amplitudes were in the range of 35 to 50 μm and the test medium was distilled water kept at 20 °C. A dummy probe is attached to the vibrating horn and immersed on liquid. As the horn vibrates it creates a cavitation zone due to the pressure variation. This test is described in the ASTM standard G 32. In each cycle, there is nucleation, growth and collapse of a cloud of bubbles. The experimental arrangement is show in Figure 1.

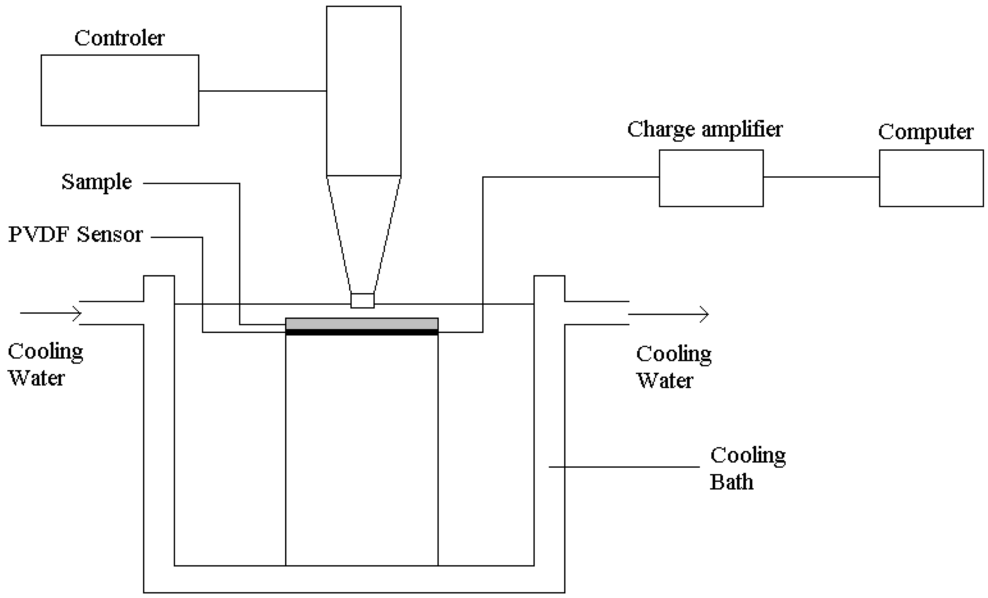

Figure 1: Schematic of the cavitation test

The material used in the present paper is a Aluminum plate of 2.45x12x62 mm. This material was chosen due to its low cavitation erosion resistance providing results in a relatively short time. The test sample was held stationary at 2 mm bellow the vibrating horn. Before the tests, each sample was grinded up to 600# to assure the same surface condition in each test. Four mass loss tests were performed at vibration amplitudes of 35, 40, 45 and 50 μm with duration of 1 hour each. After that period, its mass loss was determined with precision of 0.1 mg. Additionally, tests with longer exposition were performed with new samples. In this tests the mass loss cures were obtained interrupting the tests at regular time intervals and measuring its mass loss.

The PVDF sensor was placed bellow the cavitation zone and underneath the Aluminum plate. The dimension of the sensor is 12 x 62 mm (same as the Aluminum plate).

The data acquisition was performed at vibration amplitudes ranging from 35 to 50 μm with a 1 μm increment at 100 kHz sampling frequency. The signal was filtered in two steps. First, it was used a Butterworth filter of order 10, with 10 kHz cut-off frequency. Them the signal was decimate at a sampling frequency of 20 kHz and filtered with a FIR filter of 167 order with a cut-off frequency of 4kHz, and finally decimate at a sampling frequency (f_s) of 10 kHz.

For each vibration amplitude, the Power Spectral Densities (PSD) was calculated (Proakis *et al*, 1996) by the welch method with a Hanning windowing and 100 averaging (to emphasis the stationary part of the signal) with a 256 points (N)for each segment of the signal. The frequency resolution of PSD is given by Eq 1

$$\Delta f = \frac{f_s}{(N-1)} R_{bin} = 59 Hz \qquad (1)$$

where the R_{bin} is the resolution loss caused by the windowing type. For the Hanning window, R_{bin} = 1.5 (Harris, 1978).

3 RESULTS AND DISCUSSION

3.1 Mass Loss

The most common way to describe the behavior of a material subjected to cavitation erosion is to present its mass loss curves or mass loss rates. The mass loss rate for Aluminum samples in two different amplitudes is depicted in Figure 2 and Figure 3.

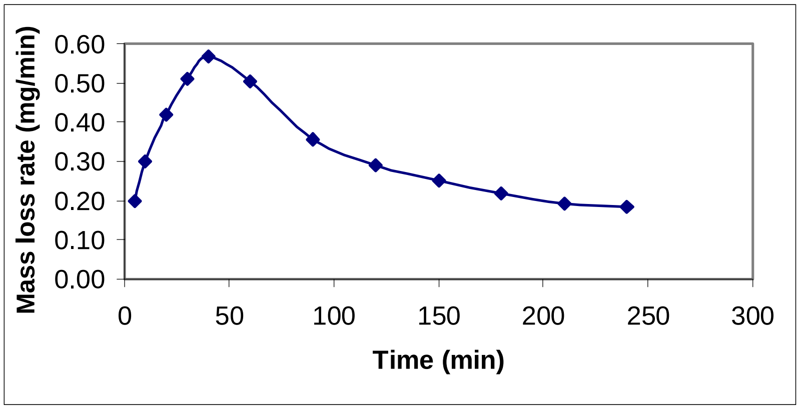

Figure 2: Mass loss rate for Aluminum sample at 35 μm

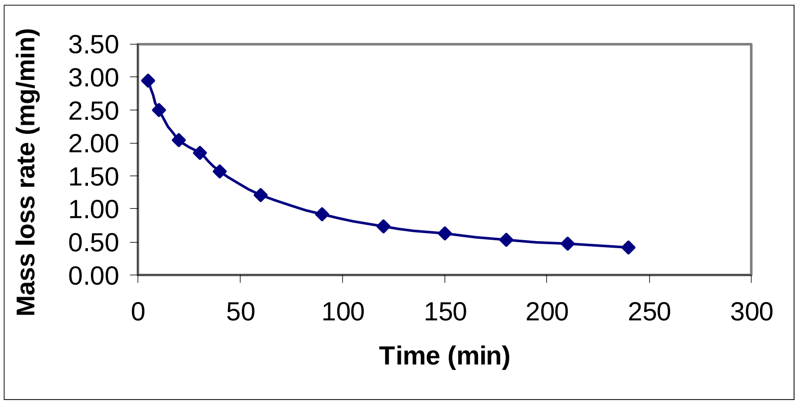

Figure 3: Mass loss rate for Aluminum sample at 48 μm

Comparing Figure 2 and Figure 3 one can see that the mass loss rate is not constant and the behavior indicated by these plots are different. The wear rates curves for cavitation tests can show at least three different regions (Karimi and Martin 1986). Initially there is a region where there is a low mass loss rate or even no mass loss at all, called the incubation period. Following the incubation period there is an acceleration period where the mass loss rate increases to a maximum and after that decreases showing a stabilization tendency. For the test with 35 μm in the initial stages, the mass loss rate is low and them increases and finally decreases slowly. With the 48 μm amplitude test, there is no incubation period and no acceleration period opposed to the 35 μm test. These results indicate that the wear rate increases with the amplitude of the vibration.

To verify this assumption tests with 1 hour duration were performed. Figure 4 shows the mass loss results for tests with 1-hour duration.

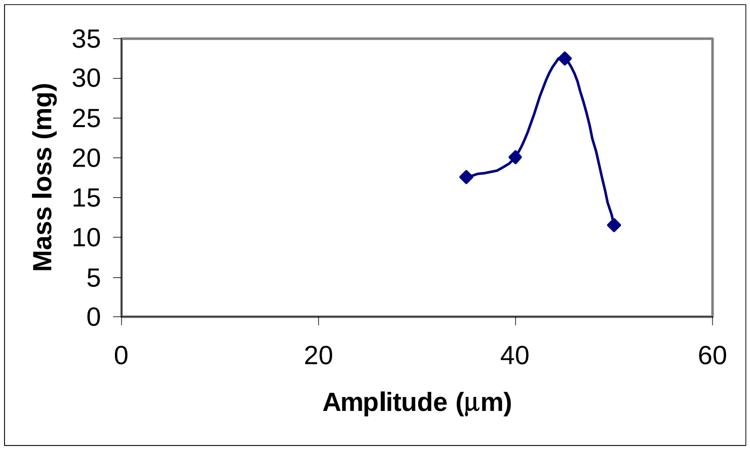

Figure 4: Mass loss after 1-hour exposure tests for the Al sample

The results are quite surprising. As can be seem the mass loss increases with the amplitude and it has a maximum at 45 μm. With amplitudes above that value, the mass loss shows a steep reduction. It is known (Preece) that changes in amplitude and frequency can affect the wear rate of a sample in a vibratory device. Vyas and Preece (Vyas and Preece, 1976) using a technique similar to the one used here verified that increasing amplitude cause an increase in the stress produced in a stationary sample. Higher amplitudes produce higher under pressures, which in turn allow the bubbles to grow to a higher radius. Since the collapsing pressure depends on the maximum radius of the bubble (Rayleigh, 1917) the collapsing pressure increases with amplitude.

So far, this has been adopted as a rule and most of the cavitation tests are performed in high amplitudes such as 50 μm, as recommended by the ASTM standard. However, the results presented above are in contradiction to that rule. It shows, at least for Aluminum samples, that the mass loss is higher for lower amplitudes.

3.2 The PVDF Sensor Results

In order to try to explain that result it is necessary to analyze the sensor response during the test. Figure 5 shows the power spectral density of the signal for Aluminum sample.

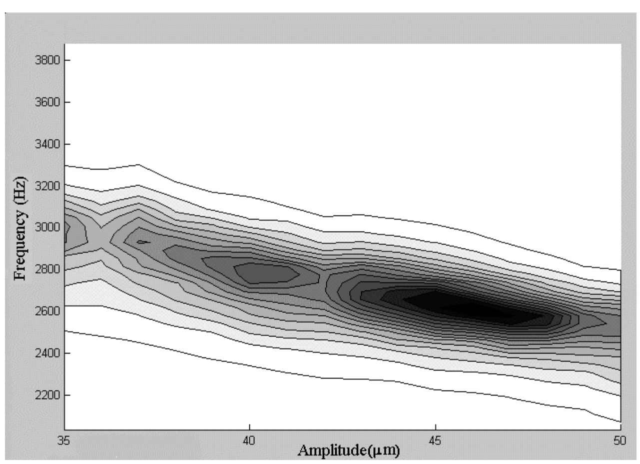

Figure 5: Spectral density of the signal for the Aluminum sample.

As can be seem from Figure 5, the sensor has a higher output voltage at amplitudes around 45 μm and lower around 35 and 50 μm. This result agrees well with the results obtained for the mass loss test and higher the excitation higher the mass loss. This test was repeated for two different materials: stainless steel and carbon steel. The spectral densities obtained for this two materials is shown in Figure 6 and Figure 7

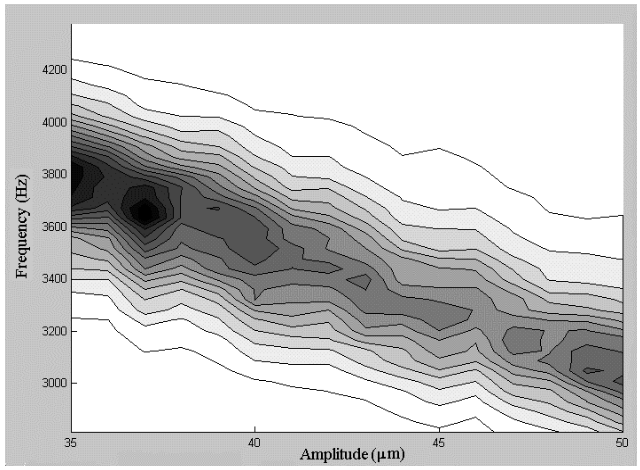

Figure 6: Spectral density for the stainless steel sample

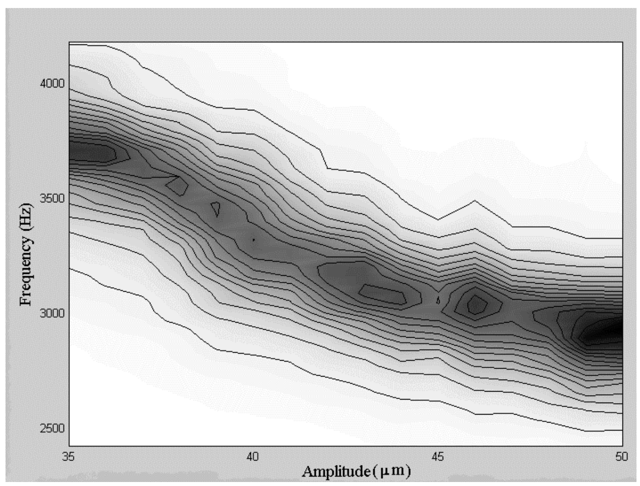

Figure 7: Spectral density for the carbon steel sample

The results show that the high cavitation intensity for the stainless steel is in the region of 35 μm and for carbon steel in the region of 50 μm. Although the mass loss tests were not performed, it is expected that the wear would be higher if the materials were tested at these conditions. Based on the results one can say that each material has a characteristic operational condition, which produces higher or lower mass loss in a vibratory test. Consequently, the general statement of higher amplitude resulting in a higher mass loss is not always true.

All PSD charts indicate a frequency band of the cavitation process between 2800 - 3800 Hz. The frequency response is high for low amplitudes and decreases with increasing the amplitude in a linear manner. This behavior is common to all materials tested. The frequencies observed in the test are connected to linear ressonant frequency of the bubbles. This frequency can be calculated by Eq 2: (Morch, 1979).

$$\omega_0^2 = \frac{3\gamma p_0}{\rho R_0^2} \tag{2}$$

Where γ is the polytropic expoent of the gas (γ=1.0 for isothermal behavior and 1.4 for adiabatic), ρ is the liquid density, p_0 is the vapor pressure and R_0 is the maximum radius of the bubble prior the collapse. For high amplitudes the bubbles grows to a high radius lowering the ressonant frequency. According to Brennen (Brennen, 1995) the ressonant frequency of a single bubble is around 5 kHz. This formula above can be used for a single bubble collapse and does not take into account several factors such as the interactions of neighboring bubbles. Therefore, the frequency values measured here seem to be in agreement with the theoretical predictions. It is interesting to observe that the ressonant frequency depends on the vibration amplitude and the material has little influence on that frequency.

4. CONCLUSIONS

For cavitation erosion tests in vibratory devices there a connection between the amplitude and material used. The general rule of high amplitudes leading to a higher mass loss is not always true and depends on the material being tested. This result was confirmed with the signal from the PVDF sensor.

5. CONCLUDING REMARKS

The output voltage of the sensor is somewhat proportional to the stress generated by the cavitation collapse. However, we should keep in mind that the voltage output of the sensor is connected in an indirect manner to the impulsive pressure generated by the cavitation collapse. The sensor is not exposed directly to the cavitation cloud, but rather to the "reaction" of the material being tested. The spectral density charts presented above indicate that each material presents a different response when tested. Further studies are necessary to understand the exact behavior of a material subjected to cavitation erosion.

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