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# Multimodal Sensing of Erosive Cavitation Phenomena

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**Abstract**—In this paper, we present a novel approach for the sensing of erosive cavitation phenomena in underwater facilities. Cavitation phenomena are known for their destructive capacity of underwater structures and are caused by the pressure decreasing followed by an implosion when the cavitation bubbles find an adverse pressure gradient. Conventional cavitation detection techniques are based on passive devices (pressure sensors or accelerometers) that just allows detection the cavitation but without assessing its erosive action. In order to go beyond these techniques that will remove this drawback, an alternative can be represented by the active techniques. Emissions of wide band signals in the flow during the apparition and development of cavitation embeds changes in the received signals. Signal processing methods, namely the Recurrence Quantification Analysis, are used to develop a robust metric that will estimate the effects of erosion.

**Keywords**—cavitation, wide band signals, spectral content, phase diagram representation, recurrence quantification

## I. INTRODUCTION

The erosive cavitation in underwater environments usually appears when the pressure drops causing the bubbles to implode when the cavitation find an adverse pressure gradient.

The conventional detection techniques are based on passive devices such as pressure sensors or acceleloremeters [1] that are limited just to the cavitation detection. The assessing of erosive behavior of the cavitation is not possible using the passive devices. In order to go beyond these techniques, the active techniques represent a viable alternative [2].

Our alternative technique proposes the emission of wide band signals in the flow during the apparition and development of cavitation. The effect of the cavitation is recorded in the received signals. This effect is highlighted using non-linear processing techniques, namely the Recurrence Plot Analysis (RPA) and the Recurrence Quantification Analysis (RQA) [3-5].

The paper is organized as follows: section 2 presents the concepts of RPA and RQA related to the study of cavitation phenomena. In section 3, we describe the experiment and we emphasize the results. Section 4 presents the conclusions and further developments of the proposed technique.

## II. SIGNAL PROCESSING METHODS

### A. Recurrence Plot Analysis

The RPA is a non-linear technique derived directly from the set of recoded data. These data-driven techniques have the major advantage that they do not use any model to analyze the data. They analyze the signal based on the organization of its samples in time.

This concept is based on the phase space representation and, as its name suggests, it highlights the recurrences of trajectories from higher-dimension phase spaces. The term of “recurrence” - one main property of conservative dynamic systems [6-11] – means that the dynamical system under study returns in a state previously visited. The method is quantified using RQA method.

The phase diagram concept starts by considering the following time series:

$$\mathbf{x} = \{x[1], x[2], \dots, x[N]\} \quad (1)$$

Then, this time series is represented in phase space. Its values become the coordinates of the  $m$  - dimensional space and, consequently, the vector sample is:

$$\vec{v}_i = \sum_{k=1}^m x[i + (k-1)d] \cdot \vec{e}_k, i = 1, M \quad (2)$$

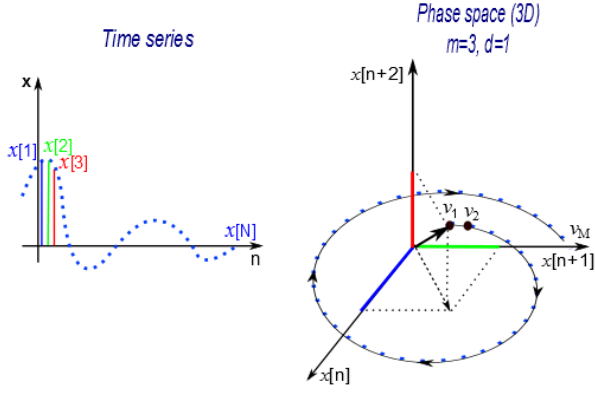


Fig. 1. The representation in the phase space using the time series  $\mathbf{X}$  [5]

where  $m$  is the embedding dimension,  $d$  is the delay,  $\bar{e}_k$  is the unit vector of the axis that defines the phase space,  $M = N - (m-1)d$  and  $N$  is the length of the time series. Usually, the embedding dimension and the delay are chosen using the false nearest neighbor method and the mutual information method, respectively [11-13].

Fig. 1 illustrates the phase space construction algorithm. Each point of the phase space trajectory has as coordinates the time series values, namely signal's samples.

Next, the distances between the vectors in the phase space are represented on the distance matrix (DM), eq. (3). When compared with a threshold, the recurrence matrix (RM) is obtained, eq. (4).

$$D_{i,j} = \mathcal{D}(v_i, v_j) \quad (3)$$

$$R_{i,j} = \Theta(\varepsilon(i) - \mathcal{D}(v_i, v_j)) \quad (4)$$

where  $\mathcal{D}(v_i, v_j)$  is a distance applied on the vectors from the phase space (Euclidean distance [10-11]), L1 norm [13], angular distance [5], scalar dot product distance [14], etc.),  $\Theta$  is the Heaviside step function and  $\varepsilon(i)$  is the threshold considered for recurrence. A graphical representation is presented in Fig. 2 when using the Euclidean distance.

### B. Recurrence Quantification Analysis

The choice of the RQA based on RPA concept for the analysis of signals coming from heterogeneous environments is based on the fact that it is a data-driven method which does not require a priori information about the system, knowing that such information is not always available [12].

The diagonal lines on the recurrence matrix indicate that the system returns in approximately the same state for a certain period of time. The choice of the diagonal lines quantification (DLQ - Diagonal Lines Quantification) is given by the fact that the distance between two successive diagonal lines provides the fundamental period of the signal [4-5].

The quantification of these lines is done as follows in eq. (5):

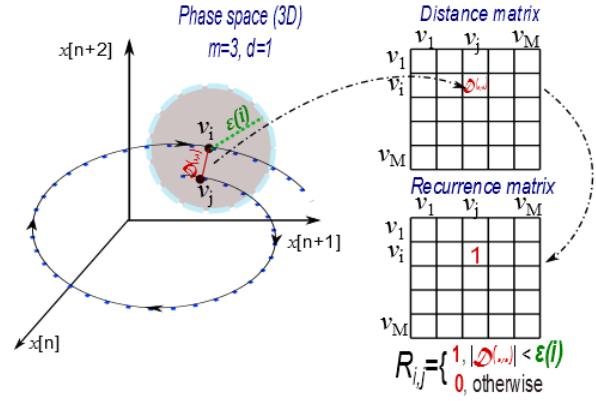


Fig. 2. DM and RM when applying the Euclidean distance [5]

$$dlq[n] = \frac{1}{M-n} \sum_{i=1}^{M-n} D^*_{i,i+n}, n = \overline{0, M-1} \quad (5)$$

where  $D^*_{i,i+n} = 1 - D_{i,i+n} / \max\{D_{i,i+n}\}$  is the complement of the distance matrix.

Then, the Fourier transform is applied to this quantification:

$$DLQ[k] = \sum_{k=0}^{M-1} dlq[n] \cdot e^{-j2\pi kn/M} \quad (6)$$

where  $M$  is given in eq. (2). Fig. 3 presents the measure applied on a sine wave with the frequency  $f = 10\text{Hz}$ .

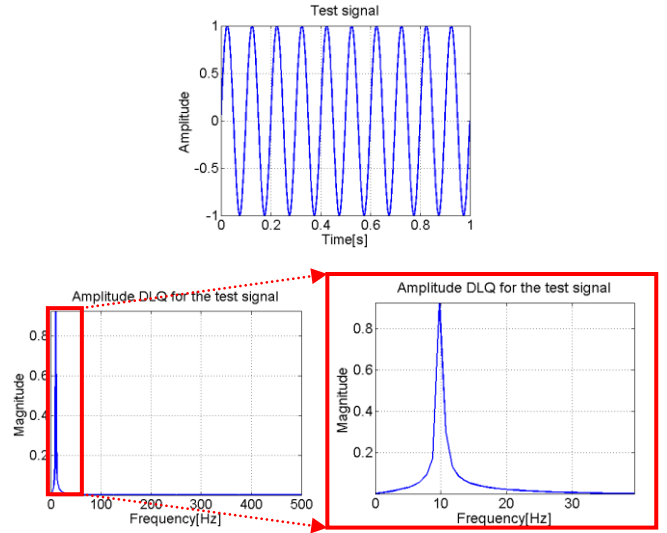


Fig. 3. Example of DLQ: (up) test signal – a sine wave with the frequency  $f = 10\text{ Hz}$ ; (down-left) the DLQ measure applied on the test signal; (down-right) zoom on the DLQ measure

This approach points out the frequency component in a different manner than the classical approach, where the Fourier transform is directly computed from the analyzed signal. In this case, the choice of the distance matrix is preferable to the recurrence matrix in order to follow the evolution of the signal

entirely and not to separate it into a binary decision which usually brings in the spectral content multiple harmonics.

We consider the Doppler effect that the erosive cavitation introduces on the emitted wide band acoustic signal [1,15]. Hereby, when  $\Omega \gg \omega$ , we study the frequency modulation spectrum using the DLQ measure. Therefore, we apply the diagonal line quantification on the next signal model (Fig. 4):

$$x[n] = \cos[2\pi f_1 n + \beta \cdot \cos[2\pi f_2 n]] \quad (7)$$

where  $f_1 = 500\text{Hz}$ ,  $f_2 = 39\text{Hz}$  and  $\beta = 2$ . The condition  $\Omega \gg \omega$  stands valid as it is the case of the erosive cavitation [1].

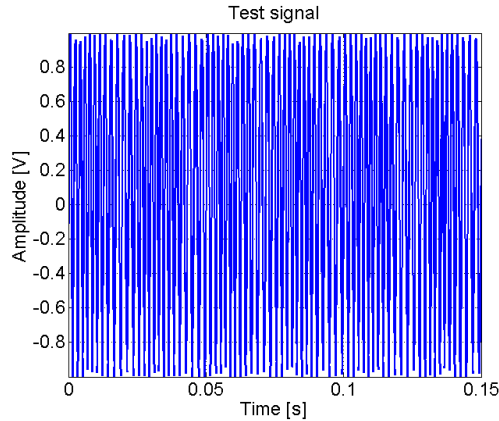


Fig. 4. The frequency modulated test signal

From Fig. 4, it can be noticed that in the case of a frequency modulated signal, the diagonal line quantification measure also emphasizes the classical components  $\Omega \pm \omega$ , but, more important, the extra component  $\omega$ . Besides an extra component  $2(\Omega \pm \omega)$  appears.

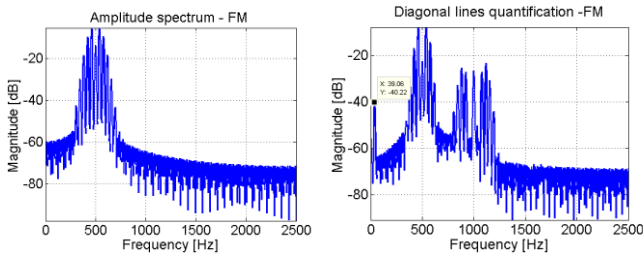


Fig. 5. The classical spectrum representation (left) and the spectral representation of the diagonal lines quantification (right); for the computation of the distance matrix, the squared Euclidean distance is used,  $m = 3$  and  $d = 2$

Using this approach, in the next section, we investigate the erosive cavitation using wide band acoustic signals.

### III. EXPERIMENT AND RESULTS

In order to test the concept of erosive cavitation detection using wide band acoustic signals, a special test facility (Fig. 6)

has been constructed. Erosive cavitation tests are conducted on metallic plates and both passive and active sensing techniques have been used. In order to produce a sufficient amount of bubbles so that the erosion effects can take place, as well as to allow the placement of sensors near the affected structure, a high power sonotrode driven by a variable power supply is used. The tip of the sonotrode was submerged in water and the resulting cavitation cloud is interacting directly on a high grade steel metal plate underneath. The sensors were installed as follows: an accelerometer was placed on the metal plate, a hydrophone was submerged in the vicinity of the plate and an underwater acoustic transducer was located underneath the metal plate in order to emit bursts of specially designed waveforms.

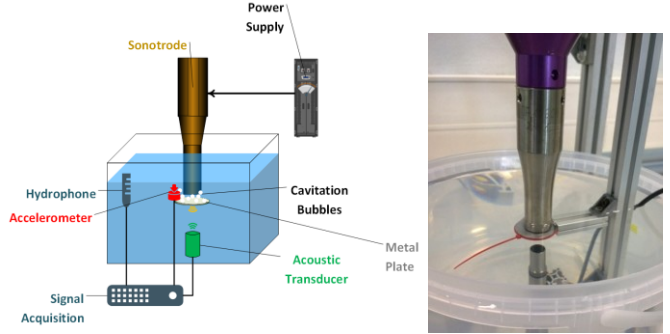


Fig. 6. The test layout for the study of erosive cavitation: (left) schematic of the experiment; (right) the experiment using the acoustic transducer signal

For the passive method, the signals, obtained from the accelerometer and the hydrophone, are used in order to make a fusion of the two. It is shown that, as the cavitation starts and increases in magnitude (more and more bubbles are created having a very high impact velocity), the signals received from these sensors pass from a narrow to a wide band spectral content, as illustrated in Fig. 7. Passive techniques are not accurate because the output signal will inherently be affected by ambient noise independent from the measured phenomena, but the overall bandwidth of the system will be scattered among the different sensors used, as described in [2] and [3].

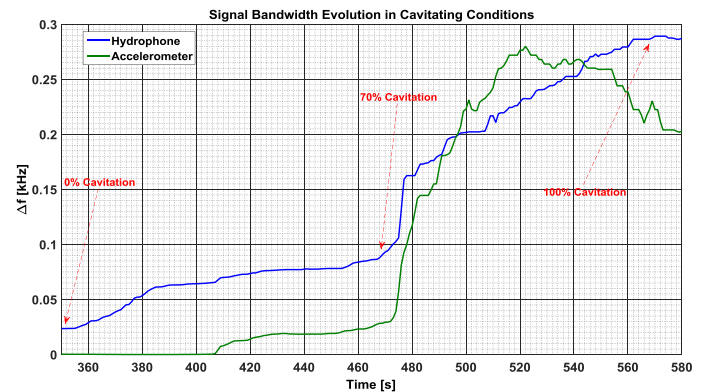


Fig. 7. Signal bandwidth evolution with cavitation – passive techniques

However, our active method based on the exploration of the phase diagram concept presents the advantage of highlighting the Doppler component that is lower than the wide band content of the emitted acoustic wave using an ultrasonic

transducer which can be placed easier than the hydrophone and the accelerometer. The latter are more restrictive regarding the investigated phenomenon.

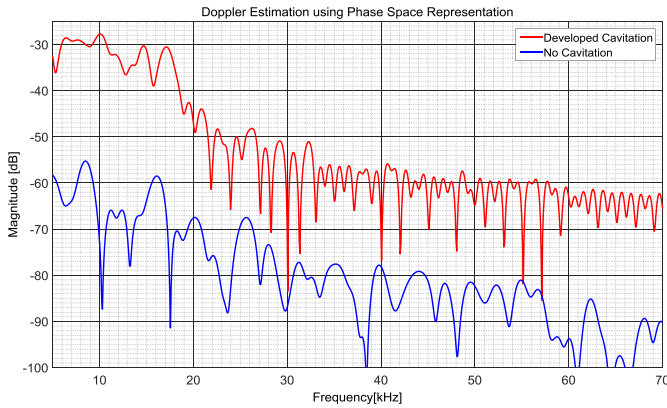


Fig. 8. Wide band Doppler effect when the cavitation is developed

The experiment is performed by emitting wide band acoustic signals in the range of  $[800 \text{ kHz}, 1200 \text{ kHz}]$ , duration of  $40 \mu\text{s}$  with the repetition rate of  $250 \text{ ms}$ .

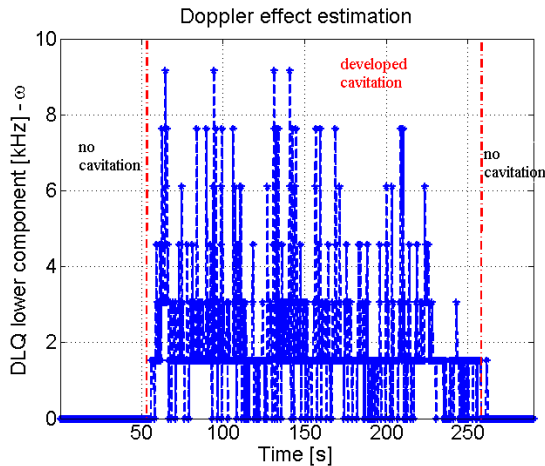


Fig. 9. The erosive cavitation detection based on the Doppler effect estimation using the DLQ measure

The results, shown in Fig. 9, point out the presence of erosive cavitation as well as its absence. In the first  $50 \text{ s}$  as well as the last  $30 \text{ s}$  the power supply from Fig. 6 is shut down. When the sonotrode is activated, the air bubbles start to appear and the received signal at the ultrasonic transducer highlights their presence when using the DLQ measure. The amplitude of the DLQ lower component is directly related to the power supplied to the sonotrode.

#### IV. CONCLUSIONS

This paper presents an alternative technique to the classical techniques for the detection of the erosive cavitation based on active wide band acoustic signals.

Firstly, the RPA and RQA methods are presented. Then the DLQ measure is described emphasizing the spectral amplitude components which are present for the frequency modulated signals.

Then, we describe the experiment and compare the results for the active configuration and for the passive techniques. It can be noticed that our proposed method points out the presence of the erosive cavitation.

Further developments will consider measurements performed on industrial sites.

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