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Detection of erosive cavitation on hydraulic turbines through demodulation analysis

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Abstract. Erosive cavitation in hydraulic turbines affects severely the runner structure, increasing maintenance costs and reducing the remaining useful life of the component. Actual vibro-acoustic techniques used to detect this kind of cavitation in hydraulic turbines are based on analysing high-frequency vibrations in different parts of the unit. Particularly, the demodulation of high frequency bands has proven to give relevant results regarding the erosive cavitation behaviour. However, demodulation is not absolutely conclusive since the excitation and the transfer function from the excitation to the measuring point, which depend on every particular prototype, are partially unknown. In this paper, the demodulation method to detect erosive cavitation in hydraulic turbines is reviewed and analysed in detail. To do so, first, an experimental study in a test rig in laboratory has been carried out. This test rig is based on a rotating disk instrumented with a piezoelectric patch and with different sensors, such as accelerometers and acoustic emission sensors, in the rotating and stationary parts. Different excitation patterns simulating erosive cavitation have been applied to the rotating disk. These patterns include pseudo-random excitations of different frequency bands modulated by one low carrier frequency, which model the erosive cavitation characteristics. In this way, it is possible to understand how mechanical vibrations similar to those produced by erosive cavitation are transmitted in such complex systems involving fluid and solid mediums. The knowledge obtained in the test rig helps to interpret the results obtained with demodulation analysis in prototypes. Particularly, in this paper these conclusions have been used to analyse erosive cavitation in a real Francis turbine.

1. Introduction

Erosive cavitation is a well-known phenomenon that erodes hydraulic turbine components such as turbine blades. The onset, effects and detection of erosive cavitation has been deeply investigated in the past from the experimental, numerical and theoretical point of view. Although, some characteristics of this phenomenon have been well determined, its effective detection in hydraulic machines is a very complex problem that is far from being solved now. Many techniques to detect cavitation in prototypes already exist[1], but the main point is to clearly separate cavitation from erosive cavitation, i.e. some reliable quantification of the erosivity is still required.

In the past erosive cavitation tests in hydrofoils[2, 3] and in reduced scale models[4] have been performed. In this context, the cavitation can be visually evaluated and compared with the rest of the signals acquired with different sensors. Also many research has been performed in prototypes[1, 5, 6] In all the cases sensors mainly used are accelerometers, pressure sensors and acoustic emission sensors. With an adequate signal processing, indicators related to the time domain, the frequency domain and the frequency analysis of the envelope have been obtained. Also Time Frequency diagrams have been used to analyze the problem. More recently, based on these indicators some researchers used machine learning techniques, such as neural networks[7]. Although, plenty of research has been conducted in the last twenty years and the detection of general cavitation seems to be solved, the main challenge is still to determine whether this cavitation is damaging for the machine or not[8, 9] .

There are two main characteristics that makes the problem difficult to be analyzed. On one side, the excitation characteristic of the erosive cavitation, which cannot be directly determined, excites a huge broad frequency band. Generally, many researchers concluded that these bands can have a width of several kHz, starting in the high frequency zone (above the 1kHz). In case of erosive cavitation or unstable cavities it is supposed that the dynamics of the unstable excitation characteristic is modulated by low frequency hydraulic phenomena such as Rotor Stator Interaction. This particular behavior of unstable cavities can be then theoretically detected with demodulation techniques[1, 6], although not all researches have confirmed it [5].

On the other hand, the relative position of the sensor, with respect to the position where cavitation is occurring, is also an important factor that has to be considered. The transmission path from the cavitation position to the sensor position can be through the mechanical system and/or through the fluid system, which increases the complexity of the problem. This transmission path may be determined with transmissibility tests, consisting on impacting the runner (dewatered) and measuring the response with the different sensors. Nevertheless, the transmission path for the runner in operation will change due to the effects of the surrounding flow and only exciting the runner in real operating conditions would determine the real transmission path with precision. Finally, less discussed is the fact that for the stationary sensors the relative position of the erosive cavitation location in the runner, with respect to the sensor, is continuously changing as the turbine rotates and these should be also considered when using demodulation techniques.

In order to have a better understanding of what is expected to detect when using demodulation techniques for erosive cavitation detection in hydraulic turbines, in this paper, an experimentation performed in a simplified model test rig with the purpose of determining the transmission mechanism of erosive cavitation has been performed. For this purpose, several excitation types emulating cavitation have been applied in a rotating disk test rig. The disk has been excited by means of a Piezoelectric Patch (PZT) with pseudo random excitation characteristics with and without modulation patterns. Several sensors used in prototype have been also placed to detect cavitation. In this way, the quality of the detection of the different sensors and positions has been evaluated and the expected demodulation characteristic for a prototype has been experimentally determined. Finally, the conclusions derived from this research are applied to perform a preliminary analysis in a Francis turbine where huge erosive cavitation occurs.

2. Detection of erosive cavitation with vibro-acoustic methods and demodulation technique

Firstly, the different sensors to detect erosive cavitation have to be mounted in different parts of the unit. Typical types of sensors used are accelerometers, microphones and acoustic emission sensors. Common locations for the sensors are guide vanes (in the shaft of the guide vane), the draft tube, the turbine bearing and the rotating shaft (sensors on board).

Generally, the demodulation technique is applied to high frequency bands that change with the operating condition, although a rule for the accurate definition of this band does not exist [10]. Once the band is defined, the signal is filtered with a bandpass filter. Then, the envelope of the filtered signal can be obtained by means of different techniques such as the Hilbert transform. Finally, the resulting envelope is analysed in the frequency domain by means of the FFT. The presence of some hydraulic

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frequencies, such as the RSI in the resulting spectrum may indicates erosive cavitation. More details on this procedure can be found in [1].

Regarding the demodulation technique, the following things, based on the review of previous papers, can be stated:

- There is not a general rule to select the frequency band that has to be demodulated. Instead of that, a first visual inspection of the frequency content of the signal (power spectrum of the time signal) can be made, in order to decide which bands have to be selected. If the amplitude of the band changes with the operating condition and therefore with the flow condition, this should mean that the selected band is suitable for the analysis.
- It is generally believed that, when RSI frequencies appear in the demodulation process, the cavitation is more erosive because this indicates an unstable behaviour of the cavity system forced by one of the RSI frequencies. Nevertheless, some researchers found erosive cavitation without a high modulation activity[5].
- The fact that the cavitation source moves with respect to the stationary sensor is less discussed in the analysed researches. This effect has to be considered as it can produce some modulation frequencies that could be confused with those one produced by erosive cavitation, as it will be discussed in the following sections.

3. Test rotating disk test rig

3.1. Test rig description

The test rig used for this research has been used in the past for the analysis of the dynamic response of a rotating disk[10-14] . Therefore, more details on its construction and characteristics can be found in these references. In the present case, several sensors including accelerometers, acoustic emission sensors and a microphone have been placed in the rotating and stationary frame of the test rig as indicated in **Figure 1** .

The rotating speed of the disk and the shaft is selected to 4.1 Hz. The driven motor, rotates five times faster, i.e. at 20.5 Hz. The signals of the rotating part are transmitted to the stationary frame through a slip ring system (Michigan, S10). A PZT attached on the disk (PI 876-A12) has been used for exciting the submerged and rotating structure. The excitations performed are described in the following section.

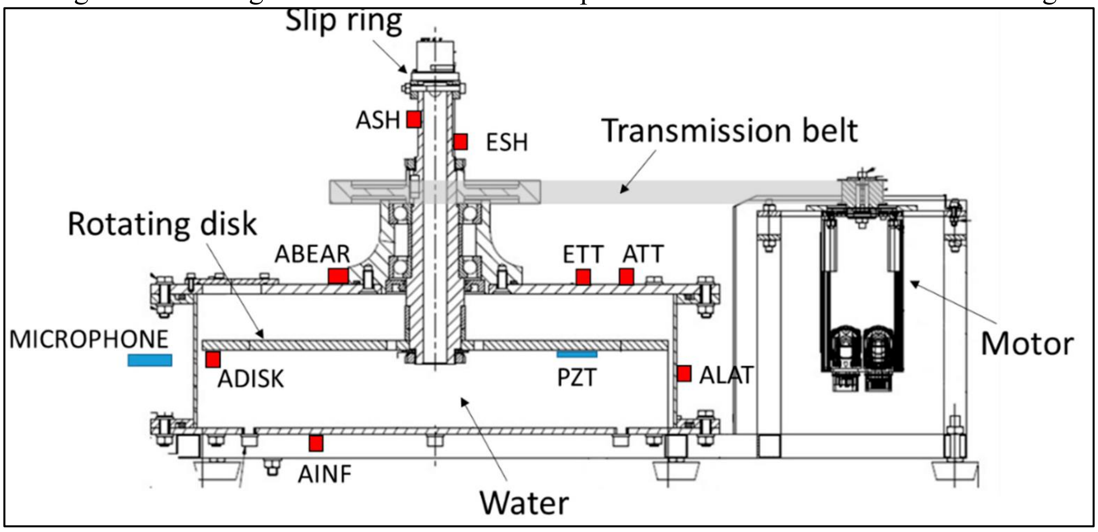

Figure 1. Test rig and instrumentation installed.

All the sensors are labeled according to the following nomenclature: A-XX means accelerometer (all of them with a sensitivity of 100mV/g), E-XX means acoustic emission sensor (B&K 8313), MICROPHONE for audible sound sensor (B&K 4957) and PZT for the piezoelectric patch exciter.

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Except the sensors ASH, ESH, ALAT and ABEAR which are mounted in a radial direction, the rest of the sensors are mounted in an axial direction.

3.2. Experimental tests performed

Two types of excitations are applied with the PZT. The base signal of these two excitations is a pseudo-random type exciting the band from *10-11 KHz* with an approximate time of 20 seconds. This excitation represents a broad band excitation (band 1 *KHz*) similar as the excitation due to cavitation in hydraulic machinery. The first excitation is simply a pseudo random excitation without any low carrier frequency(**Figure 2**a). The second one (**Figure 2**b) is also a pseudo random excitation but with a carrier frequency of 22.1 Hz. This frequency has been selected to represent a similar frequency to the RSI, i.e. a frequency higher than the rotating speed (4.1 Hz). Nevertheless, it has to be noticed that with respect to a real hydraulic turbine, this frequency has been selected to not be an harmonic of the rotating speed. This is done so, in order to clearly identify the different phenomena and distinguish rotating speed harmonics from the carrier frequency artificially created with the PZT.

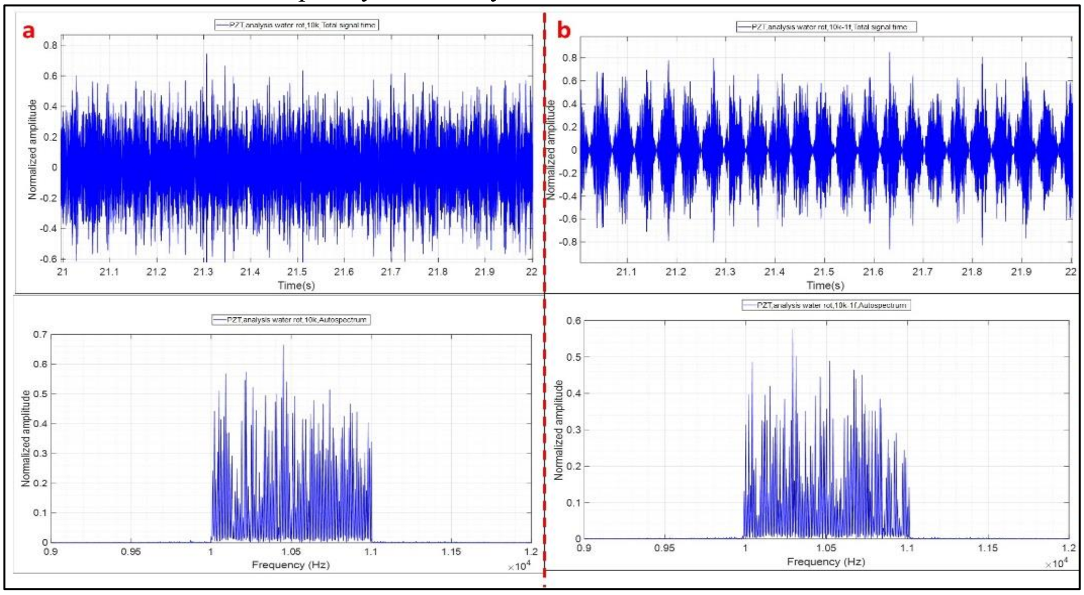

Figure 2. Excitations applied on the disk. Time and frequency domain a) Pseudo Random excitation from 10-11 KHz. b) Pseudo Random with one low carrier frequency (22.1 Hz).

3.3. Signal analysis

The signal analysis methods used in this papers are the following:

- Demodulation of high frequency band: Procedure explained in Section 2 and with more details in [1, 10]
- FRF: Frequency response function between two signals (Output/Excitation signal) according to classical definition of FRF [15, 16]
- Coherence: Coherence between two signals (Output/ Excitation signal). 1 indicates a perfect cause-effect relation or good and perfectly linear transmissibility path [15, 16].

3.4. Main conclusions obtained with the test rig

3.4.1. Sensors and location

As mentioned before, many different types of sensors and locations have been used in the past for the detection of erosive cavitation. From the comparison of many researches it is not absolutely clear which kind of configuration (sensor & location) shall be used for the detection of erosive cavitation. This is also because the transmission path from the cavitation source to the sensor cannot be determined as the excitation of the cavitating flow on the runner blades is only roughly known.

In the present test rig, as the excitation is performed with a controlled PZT, it is possible to determine which transmission path is better in terms of linear relationship with the excitation. In this case, this is evaluated through the coherence, which has been calculated for the rotating sensors (ASH, ADISK and ESH). Figure 3a shows the coherence of the sensors on the shaft with respect to the excitation. The disk was rotating at 4.1 Hz with the tank full of water. It is clearly seen that the sensor ESH is perfectly coherent to the excitation. ASH has a high coherence in the range where a wide resonance occur (see FRF in Figure 3b) but not in the antiresonant frequency bands. This is a very interesting conclusion also pointed in [10], as it shows that the acoustic emission sensor in the shaft is perfectly capable to detect all the superficial waves generated due to the PZT excitation, as the coherence is 1 for all the frequency range and the amplitude and phase of the FRF show a flat behavior. For the modulated excitation signal the conclusions are still the same.

On the contrary, the accelerometer, which is typically used in past researches, is highly influenced by the mechanical response of the shaft in this band. Therefore, it seems that the installation of an AE sensor in the shaft could be the best option to detect erosive cavitation on the blades. For the sensors on the stationary frame it is not meaningful to calculate the coherence, as the excitation is not synchronized with the relative position of the disk and therefore the transmission path changes from sample to sample. Nevertheless, it is expected that the propagation of the waves through the fluid medium will be less effective than through the solid medium.

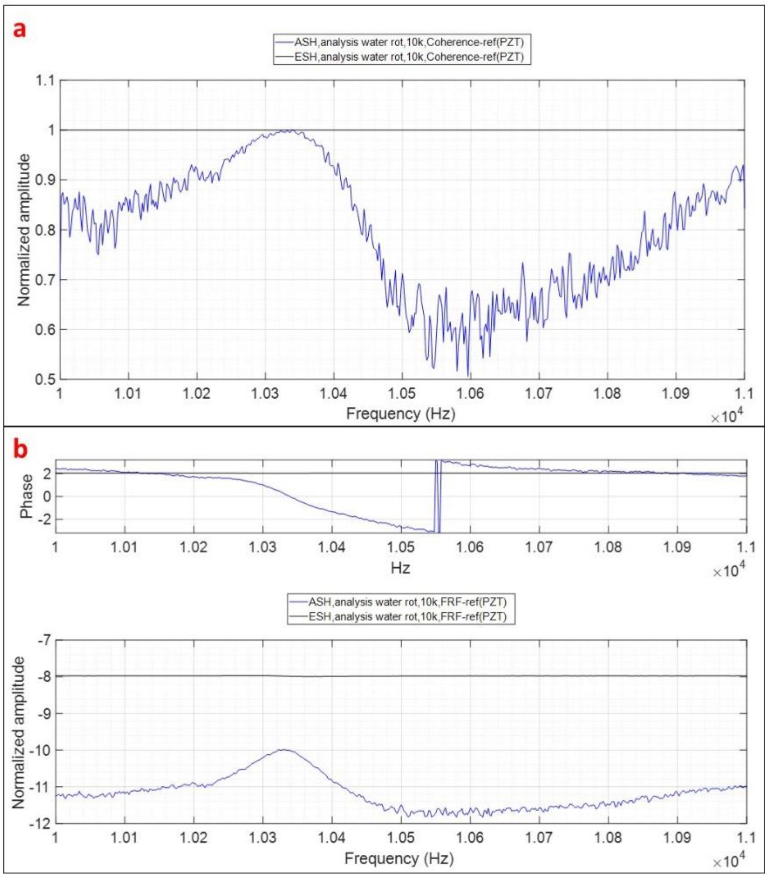

Figure 3. Coherence (a) and FRF(b) of the sensors ASH, ESH with respect to the excitation created with the PZT.

3.4.2. Detection of cavitation dynamics through demodulation technique

When the disk is excited with a pseudo-random signal without a carrier frequency it is expected that the sensors on the rotating frame do not detect any special modulation pattern. It is also expected that the sensors on the stationary frame detect a modulated signal with the rotating speed as the source is changing its relative position with respect to the stationary sensor, i.e. the PZT changes the position with respect the stationary sensors. This behaviour is observed in **Figure 4**a and **Figure 4**b (black curves).

When the disk is excited with the modulated signal (**Figure 2**b), the rotating sensor detects the carrier frequency after the demodulation procedure is applied (**Figure 4**a) a. In this situation, the stationary sensor detects both, the rotating frequency and the carrier frequency (**Figure 4**b) (blue curves). This is the second interesting conclusion because it shows that two kind of different phenomena can simultaneously detected when using stationary sensors. One is the motion of the excitation source with respect to the stationary sensor and the other is the oscillation of the intensity of the source. This second one should be associated with an oscillation of the cavity and its intensity, and therefore associated to an unstable behaviour and consequently erosive cavitation. This is discussed in the following section.

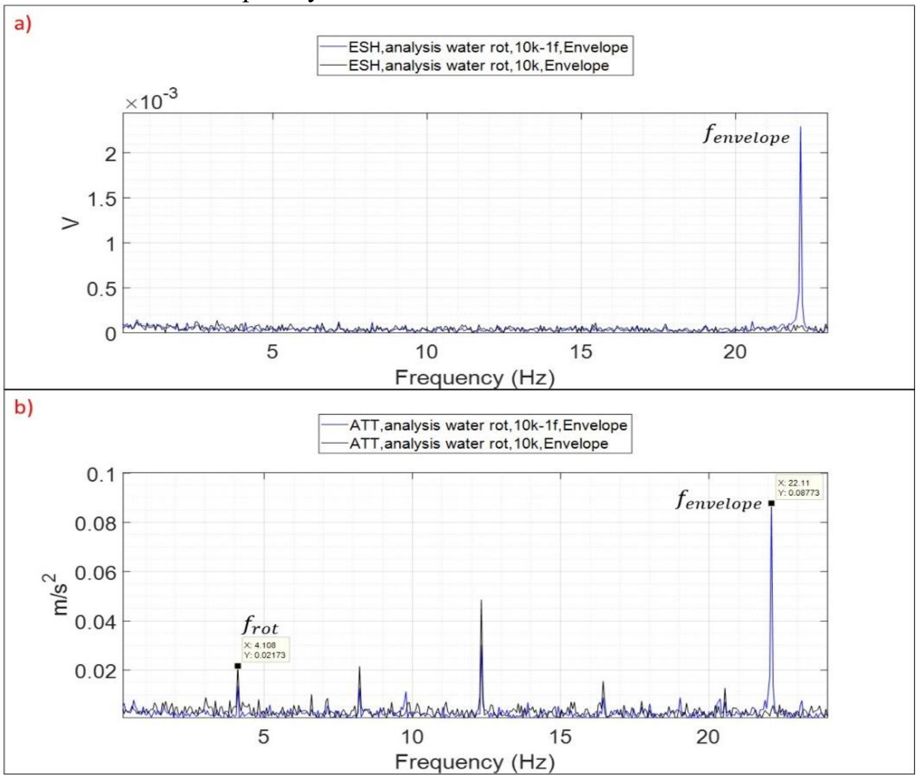

Figure 4. Modulation behaviour with a stationary and rotating sensors. a) Sensor on the rotating frame (ESH) b) Sensor on the stationary frame (ATT).

4. Assessment in prototype

4.1. Conclusions for the detection of erosive cavitation in the prototype through demodulation technique

It is well known that the pressure field inside the runner, especially at high loads, is dominated by the RSI. This is an excitation that, from the rotating point of view, has the fundamental frequency $f_v = Z_v \cdot \omega$ and higher harmonics, where Z_v is the number of guide vanes and ω the rotating speed of the runner. From the stationary point of view the corresponding frequencies are $f_b = Z_b \cdot \omega$ and higher harmonics where Z_b is the number of rotating blades. Usually, the presence of f_b in the demodulated spectrum of a stationary sensor has been associated to a high erosive cavitation behaviour[1]. Nevertheless, the analysis of the test rig results indicates that stable cavities attached to the blades would also generate this f_b frequency in the demodulated spectrum of a stationary sensor, as the cavitation source moves with respect to the sensor (see **Figure 5**). Therefore, the presence of f_b itself may not indicate an unstable cavitation behaviour.

From the rotating reference frame (for instance a sensor located on the shaft), stable attached cavities would not generate any type of modulation as they are in the same relative position to a sensor rotating with them. Nevertheless, if unstable cavities exist (represented in **Figure 5** with an oscillating motion), it is expected that they are triggered by f_v and therefore this frequency should be present in the demodulated spectrum of the rotating sensor (at least if the transmission path is coherent enough, see **Figure 3**).

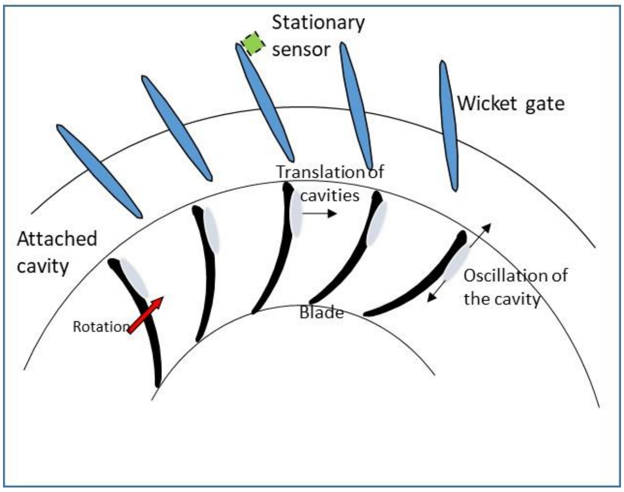

Figure 5. Motion of the source and motion of the cavity.

4.2. Example of a prototype

In a large Francis Turbine suffering from erosive cavitation a sensor on the rotating frame (accelerometer on the shaft) and a sensor on the stationary frame(accelerometer on the guide vane) have been used to detect erosive cavitation (**Figure 6**).

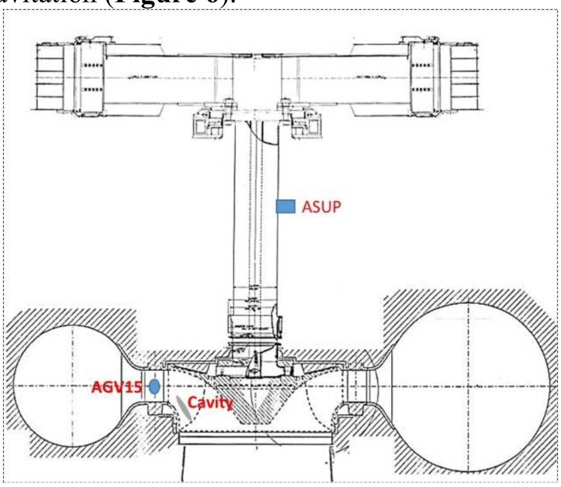

Figure 6. Sensors used in the prototype for erosive cavitation detection.

In this case, the f_b frequency can be detected in AGV15 for almost all the operating conditions. This may indicate, that the presence of this frequency in the spectrum of the envelope is not sufficient to conclude that erosive cavitation exists, as this would mean that erosive cavitation exists for all these conditions.

For one particular operating condition (85% of the best efficiency point) the machine works quite stable (no oscillation of the power) but all the sensors acquiring at high frequency (totally 12, which are not shown in this paper) showed a high RMS value. This should be related to some type of cavitation problem for this condition and therefore, it has to be analysed in detail. For higher operating powers, the RMS of the sensors decrease and is at its minimum for 115% of the BEP. In both conditions, the machine is working at a higher head than the design head (approximately 110% of the design net head), which facilitates the formation of attached cavities on the leading edge[1].

In **Figure 7**, the frequency characteristic of the envelopes for both conditions and both sensors is shown. It is seen that for the 115%-BEP condition (**Figure 7**a and **Figure 7**b), only f_b is detected in the stationary sensor. Nevertheless, as the rotating sensor does not see any type of predominant frequency, it may be concluded that no unstable cavities exist. For the 85%-BEP condition (**Figure 7**c and **Figure 7**d) the rotating sensor shows the f_v frequency which is possibly associated to the presence of unstable cavities attached on the rotating frame (runner blades) with more erosive power. Both frequencies f_v, f_b are seen in the stationary sensor, one which is more related to the oscillation of the cavities (f_v) and the other one to the translation of the cavities with respect to the sensor (f_b) . This is an equivalent conclusion to that one obtained with the rotating disk experiment (**Figure 4**).

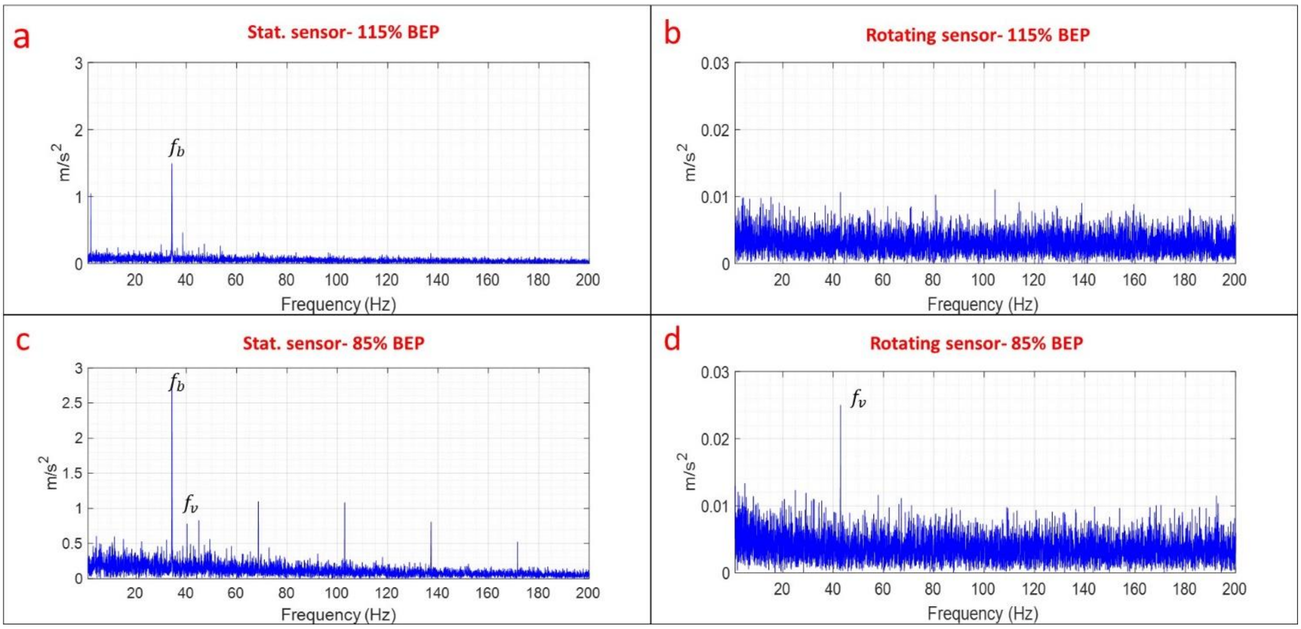

Figure 7. Spectral analysis of the envelopes of a) Stationary sensor and 115% of BEP b) Rotating sensor and 115% of BEP. c) Stationary sensor and 85% of BEP d) Rotating sensor and 85% of the BEP. Net head is 110% of the design net head for both conditions.

The time characteristic of these envelopes is shown and compared in **Figure 8** for the stationary sensor. The time is normalized so that one unit corresponds to $1/f_b$ and as the machine has 16 blades the whole time corresponds to approximately one revolution of the runner. As seen in this figure, in the 115% condition the envelope trends to follow a more flat characteristic, without very high peaks, and approximately having one maximum every $1/f_b$. For the 85% condition, which is supposed to have unstable cavities, the time characteristic show more extreme peaks which may be associated with a higher unstable behavior and collapsing of the cavities. Also, more peaks with a shorter period between peaks(as f_v also participates in the envelope, **Figure 7**c) are observed

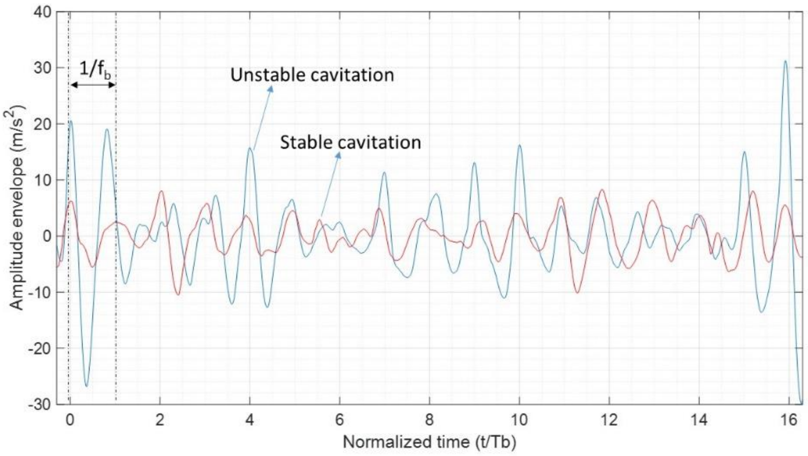

Figure 8. Time characteristic (normalized to f_b) of the envelope of the stationary sensor for the 85%-BEP and 115%- BEP condition.

5. Concluding remarks

This paper makes an experimental approach on the complex topic of differentiate erosive and not erosive cavitation with vibro-acoustic methods and particularly focused on the demodulation technique of the envelope of the high-frequency signals. The experimentation has been firstly performed in a simplified test rig and then some of the conclusions have been used to analyze a prototype, which presents erosive cavitation.

In previous researches, the demodulation technique has been used to detect erosive cavitation but some results are not very conclusive due to the following uncertainties: which sensor and where has to be placed, selection of the demodulation band and expected frequencies to be found in the demodulated spectrum of every sensor. Regarding these points, in this paper we have found that:

- The best type of sensor to detect erosive cavitation should be an acoustic emission sensor located on the rotating shaft. Nevertheless, in most of the past researches, only accelerometers on the rotating and stationary parts were used.
- Using demodulation technique two different phenomena can be identified. One is the relative motion of the cavity with respect to a stationary sensor and the other is the variation of the intensity/volume of the cavity. Usually, only this second source, which indicates an unstable cavity, is considered in previous papers to provoke modulations, which may lead to incorrect conclusions.
- The presence of f_b in a stationary sensor is not conclusive enough to affirm that high erosive cavitation exist. The information of this sensor should be ideally combined with a rotating sensor, where f_v can be expected.

In order to improve the conclusiveness of the results on the prototype, better sensors have to be used in the future (acoustic emission sensors in the shaft) and some type of advanced signal analysis should be useful to clearly identify and separate both cavity phenomena (translation and oscillation) and to better determine the transmission path.

References

[1] Escaler X, Egusquiza E, Farhat M, Avellan F and Coussirat M 2006 Detection of cavitation in hydraulic turbines *Mechanical Systems and Signal Processing* **20** 983-1007
[2] Escaler X, Farhat M, Egusquiza E and Avellan F 2007 Dynamics and Intensity of Erosive Partial Cavitation *Journal of Fluids Engineering* **129** 886-93
[3] Caron J-F, Farhat M and Avellan F 2000 Physical Investigation of the Cavitation Phenomenon. In: *6th Triennal International Symposium on Fluid Control, Measurement and*

Visualization, Sherbrooke, August 13-17, 2000, (Québec, Canada: FLUCOME 2000 the 6th Triennal International Symposium on Fluid Control, Measurement and Visualization,)
[4] Escaler X, Farhat M, Ausoni P, Egusquiza E and François A Cavitation Monitoring of Hydroturbines: Tests in a Francis Turbine Model. In: *Sixth International Symposium on Cavitation (CAV2006), 2006,* (Wageningen, The Netherlands: CAV2006)
[5] Bajić B and Keller A 1996 Spectrum Normalization Method in Vibro-Acoustical Diagnostic Measurements of Hydroturbine Cavitation *Journal of Fluids Engineering* **118** 756-61
[6] Escaler X, Ekanger J V, Francke H H, Kjeldsen M and Nielsen T K 2014 Detection of Draft Tube Surge and Erosive Blade Cavitation in a Full-Scale Francis Turbine *Journal of Fluids Engineering* **137** 011103--9
[7] Nasiri M R, Mahjoob M J and Vahid-Alizadeh H 2011 Vibration signature analysis for detecting cavitation in centrifugal pumps using neural networks. In: *2011 IEEE International Conference on Mechatronics,* pp 632-5
[8] Kumar P and Saini R P 2010 Study of cavitation in hydro turbines—A review *Renewable and Sustainable Energy Reviews* **14** 374-83
[9] Bajic B 2003 Methods for vibro-acoustic diagnostics of turbine cavitation *Journal of Hydraulic Research* **41** 87-96
[10] Valentín D, Presas A, Egusquiza M, Valero C and Egusquiza E 2018 Transmission of High Frequency Vibrations in Rotating Systems. Application to Cavitation Detection in Hydraulic Turbines *Applied Sciences* **8** 451
[11] Presas A, Egusquiza E, Valero C, Valentin D and Seidel U 2014 Feasibility of Using PZT Actuators to Study the Dynamic Behavior of a Rotating Disk due to Rotor-Stator Interaction *Sensors* **14** 11919-42
[12] Presas A, Valentin D, Egusquiza E, Valero C and Seidel U 2015 Influence of the rotation on the natural frequencies of a submerged-confined disk in water *Journal of Sound and Vibration* **337** 161-80
[13] Presas A, Valentin D, Egusquiza E, Valero C and Seidel U 2015 On the detection of natural frequencies and mode shapes of submerged rotating disk-like structures from the casing *Mechanical Systems and Signal Processing* **60** 547-70
[14] Presas A, Valentin D, Egusquiza E, Valero C and Seidel U 2016 Dynamic response of a rotating disk submerged and confined. Influence of the axial gap *Journal of Fluids and Structures* **62** 332-49
[15] Ewins D J 1984 *Modal testing theory and practice*: Research Studies Press)
[16] Heylen W 2007 *Modal Analysis Theory and Testing* (Leuven: Katholieke Universiteit Leuven)