Vibration and acoustic emission monitoring of a centrifugal pump under cavitating operating conditions

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Abstract. Centrifugal pumps are widely used in industry and cover a significant percentage of the total energy consumption of a power plant. This fact makes the application of efficient maintenance tools to be of crucial importance and obliges researchers and engineers to develop reliable detection methods for special types of malfunction, such as cavitation. Cavitation is a hydrodynamic mechanism that affects the steady and dynamic operation of a pump and is usually responsible for its head and efficiency reduction, as also for premature wear and destruction of the impeller. The stochastic nature of the phenomenon and the complex flow characteristics, as well as the noise from the mechanical components of the pump complicates the detection of cavitation. For this reason the use of several sensors in combination with advanced signal processing techniques is often proposed for the successful identification of two phase flow in the signal obtained. In this study, a radial centrifugal pump is tested under various flowrates in order to derive its cavitation characteristic curves. At the same time, the signal obtained from various vibration and acoustic emission sensors is recorded. The sensors are located at the rolling bearings that support the overhung impeller, and close to the suction of the pump, where the static pressure takes its minimum value. Subsequently, by processing the digitized signals of all noise and vibration measurements both in time and frequency domains, it is possible to identify the appearance of cavitation. Finally, the results show that the position of the sensor and the acquisition characteristics undoubtedly affect the detection of cavitation.

1. Introduction
One of the major concern of centrifugal pumps industry is related with the development of experimental tools that can detect cavitation appearance reliably and promptly. The onset of cavitation is related with the excessive drop of static pressure in the suction area of the pump that results in local evaporation, and can be due to incorrect installation of the machine, insufficient design of its impeller or operation of the pump at off-design conditions, far from its best efficiency point, where local flow acceleration or recirculation occurs that further reduce static pressure. Extensive use of a centrifugal pump under cavitating conditions can result in efficiency reduction, material and bearings wear, as well as emission of significant levels of noise and vibration. Among the numerous published works related with the
experimental study and detection of cavitating, two phase flow in hydraulic machinery, three main categories of experimental studies are distinguished: i) static pressure measurements [1-3], ii) acceleration of vibration measurements [4-6], and acoustic signals measurements propagated either in the water or solid or air with the use of hydrophones, Acoustic Emission (AE) sensors or microphones [7-14], respectively. The signal processing techniques used from the vast majority of the authors dealt either with the spectrum analysis of the raw signal or with the calculation of the powerbands of different frequency ranges and their behavior in various net Positive Suction Head (NPSH) values. Under cavitating conditions, a wide range of the frequency spectrum values are increased compare to non-cavitating conditions, indicating possible onset of the two phase flow. In addition, the simultaneous study of the internal flow characteristics with the use of visual tools, along with the values of powerbands [15], have provided a solid correlation between the intense of cavitation and the level of noise and vibration measurement.

Despite the progress of understanding of two phase flows characteristics, the aforementioned tools still cannot provide a definite answer on whether they are able to detect cavitation. The main reason is that the frequency range excited from the two phase flow differs in various pumps, because it is a function of their structural properties. According to the present authors, a step forward on the detection of cavitation in hydraulic turbomachinery is the use of signal processing techniques, which penetrate into the signal recorded and extract information that could be associated with cavitation physical characteristics. In this study, a centrifugal pump is tested under cavitating conditions, and vibration and AE measurements are obtained at the bearings and the casing. Furthermore, the frequency analysis of the signals is potentiated with the use of spectral kurtosis tool [16-18] in order to distinguish the transient information of the signal, which is related with the two phase flow. The results presented in this article show that the utilization of this methodology provides conclusions in the desirable direction, as it is able to locate the transient behavior, apply the adequate filter in the original signal, and bring out the information related with cavitation.

2. Experimental set up
The experimental set up is presented in figure 1, where the pump, the motor and the sensors used for the measurement of noise and vibration are shown. The centrifugal pump has a radial impeller with five blades and uses an asynchronous motor that rotates in constant 2900 rpm. The AE sensor and two out of three accelerometers (AE sensor, BnK, PCB) use piezoelectric transducers and one accelerometer (IFM) use microelectromechanical system transducer. Three of them (AE sensor, BnK, PCB) are located at the casing of the pump and one accelerometer (IFM) at pump’s bearing.

![Test set up, i) AE sensor, ii) PCB, iii) BnK, iv) IFM, v) pump, vi) motor](image)

Figure 1. Test set up, i) AE sensor, ii) PCB, iii) BnK, iv) IFM, v) pump, vi) motor

The procedure for the derivation of cavitation curves as well as the equations used for the calculation of the NPSH and the total head followed ISO 9906:2012 [19] (paragraphs B.5.3. and A.4. respectively) and their corresponding uncertainties equations are the same with those described in detail in [15]. The total relative uncertainties, $f_i$ for all the measured and calculated quantities related with the calculation of the characteristic curves of the pump are presented in Table 1.
Table 1. Total relative uncertainty of the measured and calculated quantities.

|                | Measured variables | Calculated variables |
|----------------|--------------------|----------------------|
| \( Y \)        | \( Q \)            | \( P_{\text{static,suc}} \) | \( P_{\text{static,dis}} \) | \( \omega \) | \( \text{Temp} \) | \( \text{NPSH} \) | \( H_{\text{TOT}} \) |
| \( f_{Y,Y} \) [%] | ±1.40             | ±0.25               | ±0.14               | ±0.10       | ±0.36       | ±0.30       | ±0.70       |

During cavitation testing of the pump, noise and vibration measurements were obtained. Each vibration sensor has different frequency measuring range and this resulted in different sampling frequencies and low pass filters at each accelerometer. The vibration signals were digitized with the use of a NI USB-9233 card that implemented the low pass filter’s cut off frequency at the half value of the sampling frequency. The noise signal was digitized with the use of a NI PCI-6052E card and a band pass filter that allows to pass only the frequency information in the range of \([2.5-80]\) kHz was used. The sampling frequency, \( f_s \), the cutoff frequency, \( f_{\text{cutoff}} \), the acquisition time, \( t_{\text{acq}} \) and the frequency range \([f_{\text{min}}-f_{\text{max}}]\) for each sensor are given in table 2.

Table 2. The values of \( f_s, f_{\text{cutoff}}, t_{\text{acq}} \) and \([f_{\text{min}}-f_{\text{max}}]\) of each sensor.

|                | BnK   | PCB   | IFM   | AE    |
|----------------|-------|-------|-------|-------|
| \( f_s, f_{\text{cutoff}} \) [kHz] | 16.6, 8.3 | 25, 12.5 | 10, 5 | 100, 80, 1 |
| \( t_{\text{acq}} \) [s]              | 10 | 10 | 10 | 10 |
| \([f_{\text{min}}-f_{\text{max}}]\) [Hz]  | [0-10000] | [0.2-15000] | [0-6000] | [2500-8000] |

3. Results

Initially, the characteristic curves of the pump are presented in figure 2, where the head and the cavitation curves for two flowrates, \( Q_1=6.1\text{m}^3/\text{hr} \) and \( Q_2=18\text{m}^3/\text{hr} \), are shown. The head curve of the pump presented typical characteristics of centrifugal pump, where the head increased with the throttling of the flow. Similarly, the cavitation curves of \( Q_1 \) and \( Q_2 \) present the stable head value at high NPSH operating points and its collapse under cavitating conditions. The drop of the head occurred at higher NPSH values for \( Q_2 \) compare to \( Q_1 \), because the higher velocity value, for higher flowrates, strengthens the development of the two phase flow at the suction of the pump.

![Figure 2](image)  
**Figure 2.** Head (green) and cavitation curves of the pump, for \( Q_1 \) (red) and \( Q_2 \) (black).

In figure 3 the frequency spectrum of the BnK’s vibration signal is given at operating points \( Q_2a \), \( Q_2b \) and \( Q_2c \). These operating conditions correspond to normal, intermediate and cavitating conditions, as it is shown in figure 2, respectively. Here, the frequency amplitude increases with the decrease of NPSH and confirms the results of several authors [2, 5, 6, 11 & 15] who related this behaviour of the spectrum with cavitation appearance. Equivalent spectrums appeared at the results of all sensors, no matter their position, however they are omitted here for brevity reasons. Furthermore, the powerband value, in the range of \([4-5]\) kHz, for the NPSH values of figure 2 is calculated for both \( Q_1 \) and \( Q_2 \) and shown in figures 4 and 5 for the vibration and AE sensors, respectively. The selection of the \([4-5]\) kHz range was based on the results presented in figure 3, where this range appeared the strongest increase at low NPSH values for all the sensors. Results that correspond at higher frequency ranges for the AE
measurements are not presented because powerbands did not increase with the lowering of NPSH value, probably due to special testing conditions, such as motor’s rotational speed and flow turbulence. In addition, the intention to present the same range for all the sensors set the upper limit of the range to coincide with the $f_{\text{cutoff}}$ of IFM sensor that was 5 kHz. According to the accelerometers powerbands, vibration level was generally increased at the bearing location, as a result of the concentration of all forces, structural and hydrodynamic, at this position. All vibration powerbands value increased heavily at NPSH values, lower than 3 m for Q1 and 6 m for Q2 (figure 5), where the head drop collapsed unquestionably by virtue of two phase flow development.

**Figure 4.** Powerband of [4-5] kHz in vibration measurements in Q1, Q2 and in different sensors.

**Figure 5.** Powerband of [4-5] kHz in noise measurements in Q1, Q2.

Similar behavior had also the AE powerband for Q2, however, in Q1 its value seems to rise earlier, at NPSH=5m, and then decreases again before the final increase at NPSH =2m. The authors are familiar with this behavior that is related with the development of two phase flow area and the noise absorption that consequently results [7, 9, 10 & 11]. After careful examination of the results of vibration for Q1 in figure 4, we observe an identical trend in PCB, BnK and IFM sensor results do not follow the same bias because of their mounting positions.

**Figure 6.** Kurtosis values under normal (NPSH=11.2m) conditions for BnK at Q1.

**Figure 7.** Kurtosis values under cavitating (NPSH=1.9m) conditions for BnK at Q1.

Until this point, all the results presented provided useful information about the ability of the sensors to monitor cavitation in a centrifugal pump and agree, to a great extent, with the conclusions already published. However, differences are detected in the value of the ranges used for the calculation of the powerband or the frequencies excited in the spectrum. The main source of these discrepancies is the different structural characteristics of each pump that result in the excitation of unique natural frequencies. This fact creates a clear obstacle in the effort to develop a general tool that will be able to detect cavitation in hydraulic machines. In order to overcome these difficulties, present authors prewhitened the original vibration signal and applied the spectral kurtosis tool. By this way, the characteristics of the digital band pass filter, used for cavitation detection, were calculated. In figures 6 and 7 the kurtosis value of BnK vibration signal at Q1 in normal conditions is compared with that under cavitating conditions. From these results, it is clear the increase of kurtosis value with the development of two phase flow in the machine. Similar results were calculated and presented for PCB sensor at Q2.
and are presented in figures 8 and 9. Overall, the vibration results derived in this experiment exhibited the same trend regardless their position and flowrate. The values of level and frequency of the maximum kurtosis are taken from the kurtosis graph and are used for calculation of the magnitude and the central value of the range of the band pass filter that is applied to the prewhitened signal.

The Fast Fourier Transformation (FFT) of the filtered PCB’s and BnK’s signals is presented under normal and cavitating conditions in figures 10 and 11, respectively. In figure 10, in both FFTs the rotational frequency (RF ~48Hz) mainly appears and its magnitude ranges between $[1-3\cdot10^{-6}]$. On the other hand, under cavitating conditions, the FFTs of both sensors present the dramatic increase of the blade passing frequency (BPF ~242Hz), which dominates the signal and its magnitude increases over one order of magnitude. This behavior of the spectrum is presumably the result of the interaction between pressure wave impulses that collide with the rotating blades. The analysis of Q1 flowrate showed that cavitation excited BPF at both PCB and BnK sensors. However, the BPF did not appear in IFM sensor, irrespective of the flowrate, probably due to its position, since mechanical sources of vibration seem to complicate the detection of two phase flow.

**Conclusions**

In this study, two phase flow in a centrifugal pump impeller is monitored with the use of AE and vibration sensors located in various position. The results of the sensors in the frequency spectrum and in the powerband of [4-5] kHz allow to discern the development of cavities in the pump and confirm the ongoing research. Moreover, the use of spectral kurtosis is proposed by the authors in order to extract additional information regarding the identification and classification of cavitation signal. According to the results, spectral kurtosis is able to extract the transient content of the vibration signal and associated cavitation with the blade passing frequency of the impeller of the pump.

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