Detection of cavitation vortex in hydraulic turbines using acoustic techniques

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Abstract. Cavitation phenomena are known for their destructive capacity in hydraulic machinery and are caused by the pressure decrease followed by an implosion when the cavitation bubbles find an adverse pressure gradient. A helical vortex appears in the turbine diffuser cone at partial flow rate operation and can be cavitating in its core. Cavity volumes and vortex frequencies vary with the under-pressure level. If the vortex frequency comes close to one of the eigen frequencies of the turbine, a resonance phenomenon may occur, the unsteady fluctuations can be amplified and lead to important turbine and hydraulic circuit damage. Conventional cavitation vortex detection techniques are based on passive devices (pressure sensors or accelerometers). Limited sensor bandwidths and low frequency response limit the vortex detection and characterization information provided by the passive techniques. In order to go beyond these techniques and develop a new active one that will remove these drawbacks, previous work in the field has shown that techniques based on acoustic signals using adapted signal content to a particular hydraulic situation, can be more robust and accurate. The cavitation vortex effects in the water flow profile downstream hydraulic turbines runner are responsible for signal content modifications. Basic signal techniques use narrow band signals traveling inside the flow from an emitting transducer to a receiving one (active sensors). Emissions of wide band signals in the flow during the apparition and development of the vortex embeds changes in the received signals. Signal processing methods are used to estimate the cavitation apparition and evolution. Tests done in a reduced scale facility showed that due to the increasing flow rate, the signal -- vortex interaction is seen as modifications on the received signal’s high order statistics and bandwidth. Wide band acoustic transducers have a higher dynamic range over mechanical elements; the system’s reaction time is reduced, resulting in a faster detection of the unwanted effects. The paper will present an example of this new investigation technique on a vortex generator in the test facility that belongs to ICPE-CA.

1. Introduction
The cavitation phenomena occurring in hydraulic machinery poses many challenges for both manufacturers and operators. The new demand for the turbine operation, imposed by the liberal market, requires the extension of the operation range of the existing turbines, including the operation...
at partial load. In the past, the turbines were optimized for an operation range near the best efficiency point. For this reason, when operating at partial load, the vortex rope appears and causes undesirable pressure fluctuations and vibrations than can affect the operation of the turbine and its life time, even if the resonance is not attained. The characterization of the vortex rope, by experimental and numerical means, remains a challenging research topic [1], [2] even on model scale. The prediction of the cavitating behavior on the prototype based on the transposition model—prototype is not accurate. Specific measurements on prototype are also needed. The interest in the cavitation problem will increase in the near future [3] due to the size reducing of hydraulic machinery leading to higher operating speeds that increase the output power [4], as well as operating turbines far from their best efficiency point [3]. It is therefore important to detect such phenomena before the effects produce irreversible damage to the machine or hydraulic circuit. The current literature presents a series of methods used to detect the cavitation phenomena. According to [3] and [5] there are a number of techniques that allow cavitation detection in hydraulic machinery via direct and indirect methods [6]. These methods are based on vibration measurement via piezoelectric accelerometers, audible sound analysis using microphones [6], paint removal techniques and computation fluid dynamics (CFD) for cavity formation predictions [7]. A large number of methods are therefore based on the analysis of induced signal by the hydraulic machine, namely the computation and analysis of the spectral content of the recorded signals.

These methods however exhibit certain drawbacks. Having numerous detection systems running in parallel onto the hydraulic machinery, the associated research and operating hardware becomes cumbersome. Therefore a first inconvenient is the amount of resource that goes into detecting the cavitation phenomena. Perhaps the most important inconvenient that arises resides in the fact that all techniques mentioned above are passive techniques: several systems “listen” to the signals provided by the hydraulic machine. The output signal will be inherently 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 [4] and in [6].

In today’s economic and technical context, operators need a less complex solution based on non-intrusive techniques that will solve the cavitation detection or monitoring problem. Therefore, such a system must employ as few sensors as possible, based on a robust signal processing technique. This paper will present a technique using an active signal processing technique based on a dual acoustic Transmitter/Receiver configuration using wide band signals for cavitation detection.

2. Active Cavitation Detection Technique

Active acoustic techniques have been applied successfully in hydraulics for the measurement of water flow in hydro power plants [8]. It is therefore natural that the same technique should be brought to the cavitation detection problem. The basic idea is to place two acoustic transducers on the side of the hydraulic machine and send pings of acoustic signals. If the cavitation phenomena do not occur, then the signal bandwidth should remain constant. Otherwise, as the flow rate increases, there will be an increase in the signal bandwidth. The test layout is illustrated in figure 1.

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**Figure 1.** Test layout for cavitation detection using acoustic emissions.
The next step is choosing the shape and content of the acoustic signal. Conventional passive techniques are based on narrow band sensors that leave out an important part of the information. In the case of an active detection, the signal shape and content is replaced by a wide band one.

Wide band signals have proven to be very efficient in characterizing turbulent flows [9], as the turbulent phenomena associated with turbulence is wide band. It is therefore necessary to increase the signal bandwidth in order to have a reliable detection. A previous attempt described in [6] using a distance measuring acoustic transducer did not provide results because the narrow beam did not allow signal detection. Hence, in order to achieve a signal transmission the signal power must be distributed along a larger bandwidth.

Signal detection and therefore analysis can be achieved. Since cavity detection implies both robust and precise constraints, a frequency technique is preferred over amplitude one, as presented in [9]. Successive emissions of the same wide band signal will pass through the turbulent flow inside the hydraulic circuit. At the receiving end, in the absence of cavitation, the signal bandwidth will remain constant. The apparition of cavitation will trigger changes in the signal bandwidth. As the flow increases, so does the vortex associate to the cavitation phenomena, and therefore the changes on the receiving signal become more evident.

3. Experimental set-up
The tests were carried out on a laboratory test facility belonging to the ICPE – CA. The experimental setup is a closed loop and consists in a supply cylindrical tank with a hydraulic circuit of 35 m length (figure 2). The pipe has 50 mm diameter and it is transparent in the test section. In order to create the rotational flow, a swirl generator (metallic stator) is inserted at the entrance in the test section, at 3.5 m downstream the pipe inlet. In order to produce an adverse pressure gradient, the test section is followed by a divergent conical section, with the divergence angle of 7°.

![Transparent test section](image)

**Figure 2.** Experimental setup.

The water flow is supplied by a pump providing a flow rate between 5 and 17 l/s, the test range velocity being between 2.5 m/s and 8.6 m/s. While the flow increases (as the velocity) the pressure decreases and the cavitation is developing in the swirling flow generated by the stator. The cavitation vortex volume, observed downstream the swirl generator, as illustrated in figure 3, is increasing from zero (non-cavitating vortex at 2.5 m/s) to maximum volume (at 8.6 m/s).
A pair of ultrasonic angled transducers was used in order to transmit and receive the signals. The central frequency of the transducers is 1MHz with a bandwidth of 650 kHz (width of the frequency response curve, at 3dB or 0.707 fraction of characteristic modulus at 1MHz maximum). The signal generation/acquisition layout is illustrated in figure 4.

The acoustic transducers were fixed in place in a “V” shaped configurations using chain mounts and a special acoustic gel in order to ensure optimum transmission of the signals, as illustrated in figure 5.
During the tests, the absolute discharge was measured with an ultrasonic flow meter. The discharge was varied manually in an ascending and descending order. The acoustic measurements were performed for the complete cycle tracking the cavitation evolution. Acoustic signals were recorded and analyzed for ascending and descending discharge values. The emitted signal consisted in a frequency linear modulated signal between 800 and 1450 kHz, therefore a signal bandwidth of 650 kHz, as illustrated in figure 6.

Since the experimental layout allowed for flow visualization, flow rates for which cavitation appeared or ceased were measured and recorded for comparison with the results of the analysis.

4. Results
The object of the research is to find a quantitative method that will provide an indication regarding the cavitation phenomena occurrence. This will act as a simpler predictor because of the reduced sensors involved, as well as providing a more powerful analysis method. The flow rate inside the measurement section in figure 4 varies first from 5 l/s to 17 l/s (with velocities from 2.5 to 8.6 m/s). As the flow rate varied, successive pings were recorded and the data was analyzed. The vortex apparition led to flow structure modification due to the presence of cavities (discontinuities in the water flow mass) observed by the acoustic sensors.

Considering [10], where for the cavitation coefficient determination a ±3% deviation is accepted, a similar band variation was imposed for the bandwidth of the recorded signal. If the values of recorded bandwidth related to the bandwidth without cavitation varied more than ±3%, it was considered to be due to cavitation presence. The values obtained for cavitation apparition with this criteria, were confirmed by the visual observations of the cavitation presence during the experimental works.

The result of the bandwidth variation for the first analyzed regime (the increase of discharge) is illustrated in figure 7.a. The relative bandwidth deviation curve and the limit band are presented in figure 7.b.

Figure 6. a) The time shape of the emitted signal; b) the frequency variation of the emitted signal from 800 kHz to 1450 kHz.

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Figure 7.a. shows that the signal bandwidth starts to decrease as the cavitation phenomena occurs in the section between the acoustic transducers, crossing the acoustic path. Since the cavitation starts to appear at flow velocity 3.275 m/s, the next points on the trace exhibit a 400 to 500 kHz bandwidth. After the cavitation becomes evident, there is a dramatic drop in bandwidth size, up to 100 kHz.
In the case of the decreasing flow curve, the results are illustrated in figures 8.a and 8.b.

The trace in figure 8.a shows that the bandwidth variation of the received signal is very low for a fully developed cavitation vortex (100 kHz) and it starts to rise when the vortex loses its strength, like in the previous case. Using the same criteria, the cavitation limit was found in this situation for a velocity value of 3.225 m/s, very close to the value obtained for the increasing flow regime.

Overall, results from figures 7 and 8 show that acoustic signal bandwidth decreases with the size and strength of the cavitation vortex (from 650 kHz for no-cavitation, up to 100 kHz for fully developed cavitation). There are small differences between the two traces. These differences are due to the manual control of the pump flow (the flow rate increasing/decreasing was not uniform) and to the hysteresis of the test loop.

The recorded data proved that it is possible to detect cavitation vortex apparition and also follow its dynamics. Even if the flow variation had abrupt changes, the acoustic measuring method was fast enough to track the sudden changes in flow structure – apparition of the cavitation.

Another potential useful method is the computation of high order statistical parameters. The presence of cavitation induce a significant change of turbulence level. This aspect was pointed out in classical cavitating flows [11], [12] – mixing layers and turbo machinery [13]. According to [14], one parameter is of interest in turbulence, the kurtosis or flatness. This parameter gives an indication about the distance between the signal’s distributions with respect of a Gaussian one. The computation of
Kurtosis relies on the computation of the fourth order cumulate and divide it by the square of the second order moment:

\[ kurtosis = \frac{\sum_{i=1}^{N} (s_i - \mu)^4}{(N-1)\sigma^4} \]  

(1)

where \( s \) is the input signal, \( \mu \) is the signal mean and \( \sigma \) is the standard deviation of the signal. For the two situations presented in this paper (increasing and decreasing flow rates), the results are illustrated in figure 9:

![Kurtosis Variation for an Increasing Flow Rate](image)

Figure 9. The results for kurtosis in cavitation detection.

Using the velocity values obtained from spectral analyzes, a variation of ±1 % of kurtosis (from no cavitation flow kurtosis) was determined to characterize the presence of cavitation in the flow field.

In conclusion, the two methods used together (spectral and statistic) could be used to identify the presence of cavitating flow. Also, for the future researches they will be useful for a more detailed characterization of the cavitation (as the air quantity included in the flow).

5. Conclusions

The purpose of the research efforts presented in this paper was to investigate a more robust and efficient method for detection of cavitation presence in flow through hydraulic machinery. Rather than choosing a multitude of systems and sensors, we proposed an acoustic emissions technique based on an active technique employing wide band signals. Wide band signals have proven very efficient in detection and estimation techniques applied in hydraulic situations.

A reduced scale experimental facility allowed the simulation of cavitation vortex by varying the flow rate inside a hydraulic loop equipped with a vortex generator.

Two basic techniques are developed from this test, relying on the spectral and statistical analysis of the acoustic signals.

In the case of the spectral technique, results have shown that the bandwidth of received signals decreases as the cavitation vortex increases in size and strength. The statistical analysis showed that it can also detect the occurrence of cavitation phenomena inside the hydraulic circuit.

The main advantages of the method are a reduced number of transducers and auxiliary systems and an early and robust detection.
Future work will focus on performing tests on a reduced scale model and a prototype of a hydraulic machine in order to obtain a quantitative characterization of the cavitation: detection and evolution related to the cavitation coefficient, together with characterization of the vortex structure.

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