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CAVITATION MONITORING OF HYDROTURBINES: TESTS IN A FRANCIS TURBINE MODEL

Xavier Escaler, Center for Industrial Diagnostics, UPC (Spain)
Mohamed Farhat, Laboratory for Hydraulic Machines, EPFL (Switzerland)
Philippe Ausoni, Laboratory for Hydraulic Machines, EPFL (Switzerland)
Eduard Egusquiza, Center for Industrial Diagnostics, UPC (Spain)
François Avellan, Laboratory for Hydraulic Machines, EPFL (Switzerland)

ABSTRACT

A series of tests have been put into effect in a laboratory to improve the cavitation monitoring techniques. Simultaneous vibrations and dynamic pressures have been measured in a reduced scale Francis turbine model with different types of cavitation: weak and intermittent cavitation at the blade outlet, outlet cavitation combined with intermittent von Karman cavitation, strong bubble cavitation and pulsating inlet cavitation.

The structure and the fluid-borne noise induced by cavitation have been analyzed in the time and the frequency domains. Initially, the low and high frequency signal contents have been compared for the various types of cavitation. Then, the main hydrodynamic frequencies that modulate in amplitude high frequency bands have been identified.

From the analysis of the results several conclusions can be extracted concerning the most suitable sensor, position and signal processing for detection of each type of cavitation. Besides, a detailed analysis of the processed data permits to infer some of their particular hydrodynamic characteristics that can be extrapolated to the real case for reliable identification.

INTRODUCTION

Cavitation can appear in hydraulic turbines under different forms depending on the hydraulic design and the operating conditions. In Francis turbines the main types are leading edge cavitation, traveling bubble cavitation, von Karman vortex cavitation and draft tube swirl.

Leading edge or inlet cavitation is usually a very aggressive type of cavitation that is likely to deeply erode the blades. Traveling bubble cavitation is a noisy type of cavitation that can reduce significantly the machine efficiency and provoke blade erosion. Periodic shedding of von Karman vortex cavitation at the trailing edge of blades can provoke their cracking due to vibrations under lock-in conditions. And finally, draft tube swirl generates low frequency pressure pulsations that in case of hydraulic resonance can cause strong vibrations on the turbine and even on the power-house.

These cavitation phenomena can be reproduced and visually observed during model testing in an adequate laboratory. Nevertheless, the conditions of apparition and the intensity of their undesired effects can not yet be scaled with precision to the corresponding prototype. Because of that, unexpected cavitation problems can arise during normal operation of the actual Francis turbine. Therefore, in order to detect and prevent them, it is necessary to apply adequate detection techniques that could be easily and successfully used in real hydropower plants. The use of vibrations and pressures for cavitation monitoring appears to fulfill such needs.

Up to now, many research in the field of cavitation monitoring has been carried out in actual hydraulic turbines suffering from erosion. However, it is necessary to investigate under controlled conditions the different types of cavitation that can appear in a Francis turbine in order to use these results for identification and quantification in prototypes.

EXPERIMENTAL SET-UP

The tests were carried out in a LMH-EPFL test-rig that can be operated with a maximum head of 100 m and a maximum discharge of 1.4 m^3/s.

The reduced scale model was composed of 20 guide vanes and a Francis turbine runner with 19 blades. The rotating speed during the tests was of 874 rpm approximately. The main characteristic frequencies which are the fundamental, the blade passing and the guide vane passing ones are calculated in Table 1.

Table 1: Main characteristic frequencies of the model.

Fundamental	**Blade passing**	**Guide vane passing**
f_f = rpm/60	$f_b = 19 \cdot f_f$	$f_v = 20 \cdot f_f$
14,56 Hz	276,76 Hz	291,33 Hz

Two accelerometers, A1 and A2, were installed at 180º on the turbine guide bearing in radial and in axial direction respectively. Two dynamic pressure sensors, P1 and P2, were mounted at 90º in the guide vane channels upstream the runner. And finally, two more dynamic pressure sensors, P3 and P4, were mounted at 180º on the draft tube. The location of the sensors is outlined in Figure 1.

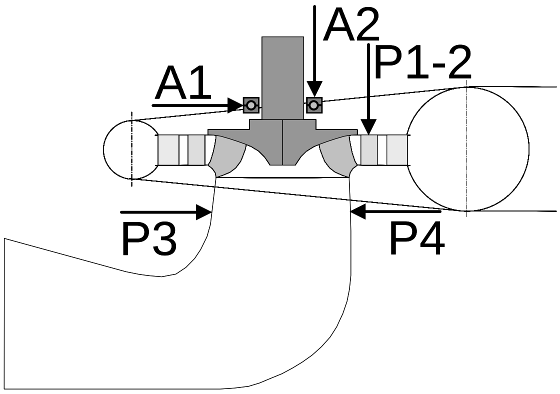

Figure 1: Outline of the measuring positions.

The output signals were low pass filtered below 20 kHz for anti-aliasing with a Chebyschev filter. A LeCroy 6810 A/D converter was used to make simultaneous records with a sampling frequency of 50 kHz per channel.

TESTING CONDITIONS

A free cavitation regime and four regimes presenting distinctive types of cavitation were tested. The operating conditions were selected by visual observations through the transparent draft tube cone with the help of an stroboscopic lamp. The operation regimes are designated by a name indicated between square brackets and they are described as follows:

1. [NO CAV]: Cavitation free.
2. [OUTLET]: Intermittent and weak outlet blade cavitation & overload rope.
3. [OUT_VK]: Outlet cavitation & von Kármán cavitation (intermittent) & overload rope.
4. [BUBBLE]: Strong bubble cavitation & overload rope.
5. [INLET]: Pulsating inlet cavitation on extrados & part load rope.

METHODOLOGY

The methodology used in this work consists in analyzing the structure- and fluid-borne noise generated during the final collapse of the vapor cavities in the form of bubbles, clouds and/or vortexes. The structure-borne noise is measured with high frequency accelerometers mounted on the machine bearings and the fluid-borne noise is measured with dynamic pressure sensors flush mounted on the wetted surfaces of the turbine.

Due to the pulsating character of the cavity collapses and to their high production rate, frequencies above 10 kHz and up to hundreds of kHz are clearly excited when cavitation occurs. In a hydraulic machine, the generation, shedding and collapse process of vapor cavities is believed to be forced by the main hydrodynamic behavior of the flow. As a result, the vibration and pressure signals appear to be amplitude modulated by these characteristic frequencies in the high frequency range.

To detect these symptoms, the signals are analyzed on the frequency domain to identify the most sensitive frequency bands. The presence of some form of cavitation is usually pointed out by an increase of their amplitudes. Then, the raw time signals are filtered in such bands and an amplitude demodulation processing technique is applied to identify the main modulating frequency peaks. The finding of synchronous peaks at the rotating frequency, the blade passing frequency and/or the guide vane passing frequency and their harmonics can be a clear sign of the type of cavitation. The use of various sensors located upstream and downstream the runner can help to locate the region where that cavitation is occurring.

Abbot et al. (1991) were the first ones to apply the amplitude demodulation technique on large hydro turbines for erosive cavitation detection based on the good correlation found between erosion and high frequency acceleration levels. Bourdon et al. (1996) continued this vibratory approach in both laboratory models and actual prototypes but mainly concentrated in erosive leading edge blade cavitation. Later on, the same author (Bourdon et al. 1996) leaded a deeper investigation which found significant differences between the model and the corresponding prototype in terms of cavitation erosion. It was concluded that the flow behavior of the model should be different than that of the prototype. Thus, the strong influence of the particular turbine hydrodynamics was confirmed. More research work was carried out by Vizmanos et al. (1996) and Escaler et al. (2002) to asses the previous findings with successful results. Nowadays, the use of advanced instrumentation for on-board measurements on rotating shafts of prototypes is being investigated (Escaler et al. 2003). Nevertheless, the main research on prototype cavitation detection has been devoted to erosive leading edge cavitation. So, there is a lack of experience on the use of these techniques for other important types of cavitation such as bubble, outlet and von Kárman.

RESULTS AND DISCUSSION

At the top of Figure 2, the power spectra of the vibrations measured on the bearing in radial direction (A1) are plotted for all the operating conditions. The high frequency content up to 25 kHz shows different levels of excitation depending on the type of cavitation. The largest amplitudes appear when strong bubble cavitation takes place. A similar behavior but with lower levels is found for the bearing vibrations in axial direction as shown at the bottom of Figure 2.

The most significant results regarding the dynamic pressure measurements have been found on the draft tube. The power spectra of sensor P4 are plotted on Figure 3 for the various regimes. In this case, the largest excitation is found up to 15 kHz. As for the vibrations, the largest amplitudes are detected for bubble cavitation but in the low frequency range below 5 kHz. It is interesting to note that for this condition two single peaks at the blade passing frequency and its second harmonic predominate over the entire bandwidth.

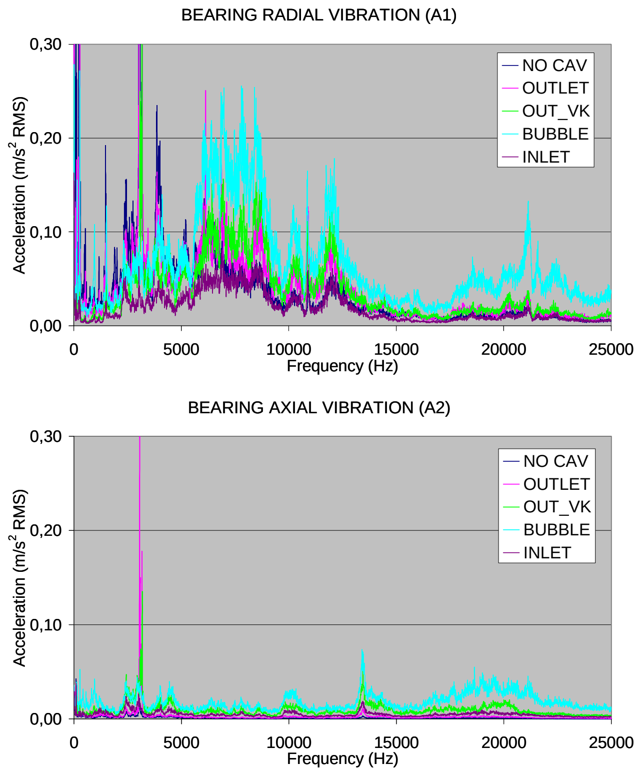

Figure 2: Power spectra of bearing vibrations in radial direction.

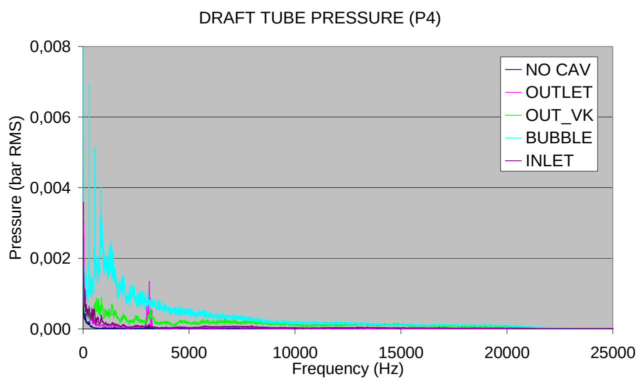

Figure 3: Power spectra of draft tube dynamic pressures.

The overall values of vibrations in A1 and pressures in P4 have been evaluated in two frequency bands, a large one from 1 to 19 kHz and a narrow one from 10 to 15 kHz. These results are listed in Table 2. The figures show an analogous trend for both magnitudes, acceleration and pressure, in the high frequency band. In this case, the regimes are ordered in terms of increasing amplitudes starting with no cavitation condition, then followed by inlet cavitation, outlet, outlet & Kárman and finishing with bubble cavitation which shows the largest values.

Therefore a frequency band between 10 and 15 kHz has been chosen to filter the signals prior to the computation of the envelope for amplitude demodulation. The technique is purely digital and it is based on the Hilbert transform (Escaler et al. 2006).

Table 2: Overall values of vibrations and pressures.

Position/unit	**A1 m/s^2 RMS**		**P4 bar RMS**	
Band (kHz)	**1-19**	**10-15**	**1-19**	**10-15**
NO CAV	3.1	0.6	0.0003	0.00006
OUTLET	5.5	1.0	0.0030	0.00043
OUT_VK	2.6	1.2	0.0079	0.00287
BUBBLE	4.1	1.9	0.0223	0.00368
INLET	1.3	0.6	0.0023	0.00080

In Figure 4 the modulation spectrum obtained with the cavitation free regime is compared with analogous results obtained with outlet and outlet & Kámarn cavitation regimes for the bearing vibrations in radial direction (A1). In Figure 5 the same is done for bubble and inlet cavitation regimes. Note that the reduced frequency is used on the x-axis which is calculated as the ratio between the corresponding frequency and the fundamental frequency (= frequency/f_f).

In Figure 5 the amplitude modulation results for the draft tube pressure pulsation (P4) corresponding to outlet and outlet & Kámarn cavitation are plotted compared with the free cavitation one. In Figure 6 the same is done for the rest of cavitation types.

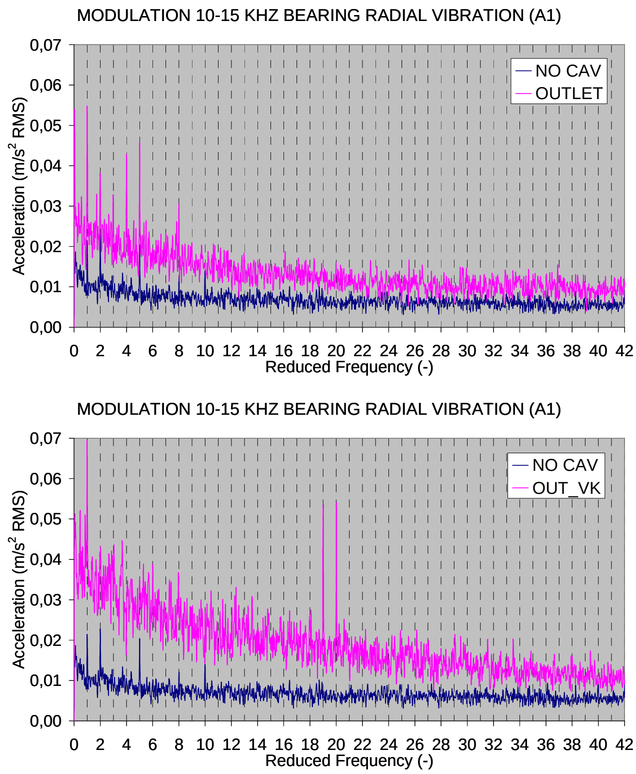

Figure 4: Comparison of free cavitation modulation with outlet (top) and outlet & Kármán (bottom) cavitation for A1.

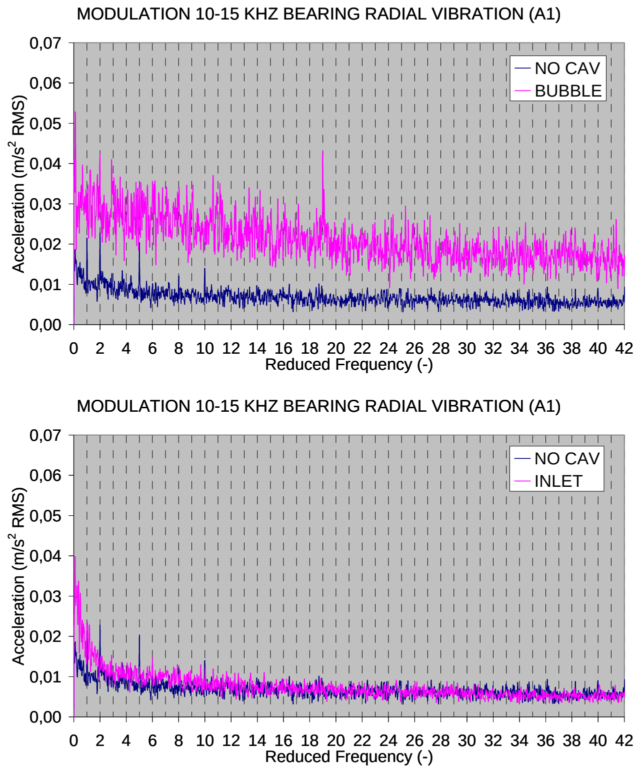

Figure 5: Comparison of free cavitation modulation with bubble (top) and inlet (bottom) cavitation for A1.

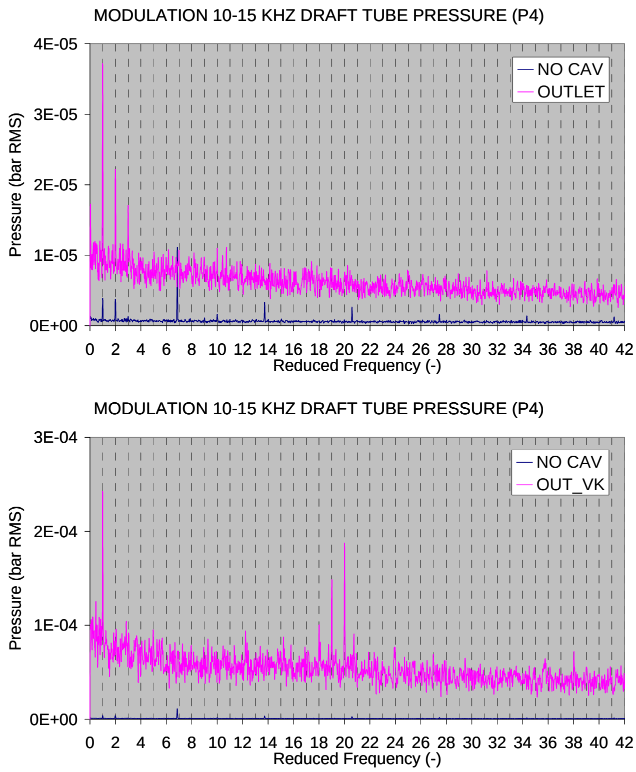

Figure 6: Comparison of free cavitation modulation with outlet (top) and outlet & Kármán (bottom) cavitation for P4.

To begin, it is observed that the apparition of any type of cavitation rises the baseline of the modulation spectra compared with the free cavitation condition. This happens in both vibration and pressure measurements. The less significant results are found for inlet cavitation and particularly on the bearing measurements. It is clear that no distinctive frequencies are found to be modulating the high frequency band in this case. On the contrary, for the rest of cavitation types, typical frequency peaks are well identified.

Bubble cavitation provokes an amplitude modulation at the f_b in A1 and at f_b and $2f_b$ in P4. The condition with outlet & Kármán cavitation shows a modulation at f_f, f_b and sidebands at $f_b \pm f_f$ in both A1 and P4. And finally, the outlet cavitation presents modulation at f_f and some of its harmonics ($2f_f$, $3f_f$, …) with no peak at f_b. The modulation spectra with no cavitation does not show any peak at f_b and harmonics but there are clear peaks at f_f and some of its harmonics.

In brief, the most relevant modulation spectrum signatures have only been identified for outlet & Kárman and for bubble cavitation conditions which were observed to have strong intensity. On the contrary, the other two types, outlet and inlet, were considered as weak forms of cavitation by the visual observations. Consequently, it is not surprising that the detection of the latter ones appears to be very difficult.

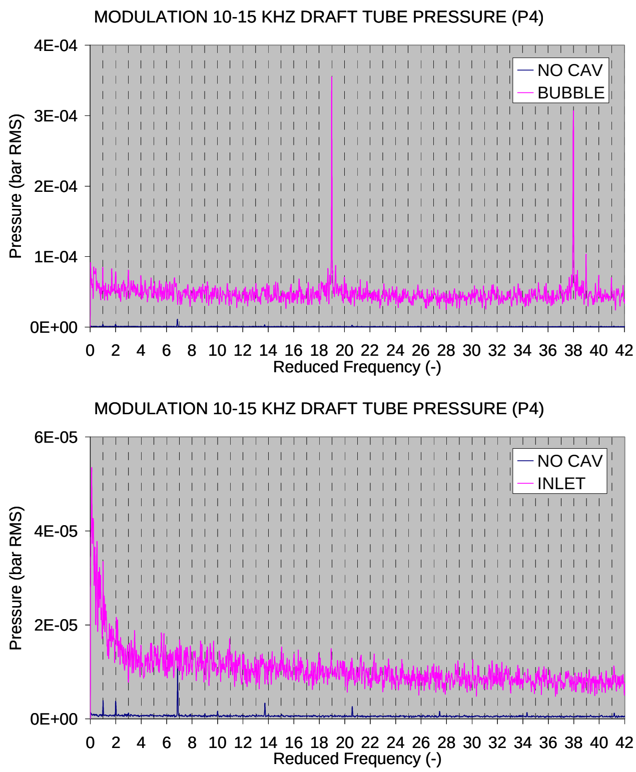

Figure 7: Comparison of free cavitation modulation with bubble (top) and inlet (bottom) cavitation for P4.

In order to clarify the origin of the main characteristic frequencies modulating the cavitation phenomena, a low frequency power spectra of the pressure pulsations in draft tube has been computed. The results from the draft tube pressure sensor P3 are plotted on figure 8 for no cavitation, outlet & Kárman and bubble cavitation. It can be seen that the cavitation modulation is induced by the main pressure pulsations dominating the machine draft tube. This seems to be logical since these type of cavitation take place at the blade outlets and downstream of the trailing edges. For outlet & Kármán cavitation, peaks at f_b and at f_b+f_f are detected as well as f_f. For bubble cavitation, two peaks at f_b and at $2f_b$ are detected which in turn appear with sideband peaks at the precession rotation frequency of the partial load vortex rope. Finally, it must be noted that with no cavitation, the f_b peak is also clearly observed.

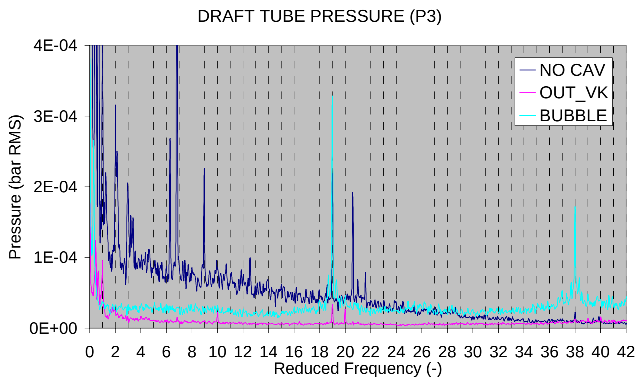

Figure 8: Power spectra of draft tube pressure with no cavitation, outlet & Kármán and bubble cavitation regimes.

CONCLUSION

Accelerations measured on the bearing of a Francis turbine model test-rig can be used to detect outlet and bubble cavitation.

Radial sensor orientation measures signals of higher amplitude than axial.

Dynamic pressures on the draft tube are more suitable than pressures measured upstream of the runner.

A frequency band from 10 to 15 kHz is suitable to analyze the high frequency content and the amplitude modulation for cavitation detection.

In these tests, both weak outlet and inlet cavitation forms have not given reliable results may be due to their low intensity.

For outlet cavitation combined with intermittent von Kármán cavitation, modulation frequencies at f_f, f_b and f_b+f_f (possibly f_v) are found.

For bubble cavitation, modulation frequencies at f_b and $2f_b$ are found.

It seems to be clear that the shedding process of vapor cavities is forced by the main flow hydrodynamic behavior. In this case, the main pressure pulsations acting on the draft tube correspond with the main modulation frequencies detected.

It is necessary to validate the current results on actual prototypes suffering these types of cavitation.

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