Utility of Acoustic Detection in Hydraulic Machinery

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Abstract. Optimised energy production from hydraulic machinery is dependant both on the care taken during the design and construction phases and on the ability to ensure optimal operating conditions. When machinery is affected by cavitation, performance levels fall and can rapidly deteriorate altogether, a phenomenon which makes it essential to identify the onset of cavitation using effective detection methods. In the present paper the analysis conducted on the basis of acoustic measurements (characterized by non intrusive technology) displays a particular sensitivity, making it suitable for detecting the phases of cavitation onset. The experimental measurements point out the presence of a marked increase in the spectral power density curve of the noise signal, especially in the high frequency range. Moreover the acoustic method also makes it possible to detect different nuclei of cavitation in the machinery under the same operating conditions (which is not achieved by other methods). These characteristics of the acoustic method are of particular interest to managers of working systems (with a view to verifying whether the working conditions can trigger cavitation) as well as to the manufacturers of hydraulic machinery (both in the design and in the production phase).

Key words

hydraulic machinery, cavitation noise, acoustic method, non-destructive tests.

1. Introduction

Hydraulic energy is a renewable, non-polluting and relatively low-cost energy source: if it is not used as and when it becomes available, the result is a lost economic benefit and damage to the environment caused by the use of non-renewable energy sources.

Hydraulic machinery thus continues to play an important strategic role in renewable energy production and it therefore seems appropriate that optimal conditions should be assured during the design and operating phases.

In certain operating conditions, hydraulic machinery such as turbines, pumps or special machinery that can operate as either turbines or pumps may be affected by cavitation, a phenomenon which causes performance levels to fall and, in particularly serious conditions, to rapidly deteriorate.

This risk has always fuelled interest in methods that make it possible to promptly detect and/or identify the onset of cavitation in hydraulic machinery [1]-[4]. As cavitation generates vibrations in the machine body accompanied by characteristic noise, methods for the direct detection of cavitation are essentially based on the detection of vibration and noise [5], [6].

Both direct methods have been shown to be highly reliable and sensitive in detecting cavitation at the moment of its onset, but the noise detection method (acoustic method) displays an entirely unique feature. This method does not require equipment sensors to interact physically with the machine because the noise can be measured by microphones positioned merely in the proximity of the machinery in question.

Moreover, the measurement equipment can be employed to explore numerous parts of the machinery or of an albeit complex system laid out over a considerable surface area.

In light of these considerations, the present paper reports experimental tests that show a second particular utility of the acoustic method for cavitation detection that other methods cannot provide.

The tests were carried out on pumping systems, which are obviously simpler and less expensive to set up in the experimental laboratory. The obtained results can nevertheless be extended to any other hydraulic machinery in which cavitation may arise.

2. Cavitation Noise

When the absolute pressure in a rapidly moving liquid falls locally to values below the vapour pressure or below the partial pressure of gas dissolved in it, the phenomenon known as cavitation occurs, resulting in the formation of bubbles of vapour or gas. These local pressure variations may arise even when there is no turbulence through modifications to the fluid stream caused by obstacles, rough walls, or changes in direction and dimension. Normally, as the bubbles move rapidly with the flow, they implode just as quickly and are

reabsorbed by the liquid when the pressure exceeds the above values.

This phenomenon is generally accompanied by high intensity pressure waves which have a brief duration and produce a characteristic noise in the high frequency domain (several thousand Hz) which may define whether cavitation is present and what its characteristics are [7]-[10]. For instance, it is possible to draw the power spectral density curve of the acoustic signal as the cavitation number σ varies (comparable to the Thoma cavitation factor) which is, of course, a pressure coefficient that decreases as the cavitation intensity increases and is defined by the equation:

$$\sigma = \frac{p - p_v}{0.5 \cdot \rho \cdot V^2} \quad (1)$$

where p is the absolute pressure and p_v , V and ρ are respectively the vapour pressure, reference velocity and density of the fluid.

It should be noted that cavitation can also occur in low velocity fluid flows where cavitation bubbles may cluster together and form larger bubbles of vapour [11], [12]. These bubbles take longer to be reabsorbed into the surrounding liquid and do not create the high-frequency noise because there is no rapid implosion: indeed there is a direct correspondence between implosions and the pulses making up the acoustic signal.

In actual fact, the cavitation phenomena of greatest interest and importance for hydraulic machinery are those concerning hydraulic turbines, such as reaction turbines working in depression, and centrifugal pumps where the impeller revolves at very high speed.

Hydraulic machinery normally reaches its highest performance level in the proximity of conditions in which cavitation can arise and therefore it is not infrequent that machinery is designed for optimal operation under conditions close to cavitation. In other words, in high performance machinery the liquid assumes high velocity values which can lead to the onset of cavitation.

Clearly if the operating conditions cause the onset of cavitation in the machinery, any and every effort in the design phase to optimise machine performance becomes pointless as cavitation results in a fall in power generated in turbines and a fall in prevalence and flow rate in pumps. Moreover, the implosion of bubbles (pressurised by the fluid flow) in the proximity of the machine wall generates pressure waves (water hammer) causing an erosion phenomenon which may also be accompanied by a form of chemical aggression (substantially due to the gas dissolved in the vapour bubbles).

All the above reasons suggest that in the presence of this type of phenomenon, particular attention needs to be paid to the most dangerous conditions corresponding to acoustic emissions for which the frequency spectra show marked rises in the high frequencies field.

In this field the cavitation detection method based on acoustic measurements appears to be particularly effective and sensitive, as environmental noise can be easily filtered out and distinguished from the high frequencies.

Moreover, the practical organisation of the measurements is extremely simple as this is based on straightforward and relatively low-cost equipment that, above all, does not need to interact physically with the machinery in question (unlike other direct methods for detecting cavitation). As a result, these can be used on different pieces of machinery in a system or even on different systems.

3. Experimental Tests

Cavitation effectively causes profound modifications in the structure of the acoustic signal: the experimental measurements point out the presence of a marked increase in the spectral power density curve of the noise signal especially in the high frequency range [7], [10], [12].

Within certain limits, the modifications to the acoustic signal can also be perceived directly by the human ear; for a complete analysis (as previously pointed out) it is necessary to use instrumentation ensuring no direct interaction with either the fluid flow or the machinery under examination.

In the acoustic measurements of the tests carried out on the pump (schematically shown in figure 1), a phonometer with a microphone and an overall 22.5 kHz passband was used. The signal picked up by the phonometer was sent to a 1/3 octave real time spectrum analyser which provided the histogram of the spectral power densities for the various frequencies investigated.

Fig. 1. Scheme of the pump.

In particular a series of thirty tests were conducted with an increasing flow rate. Figures 2, 3 and 4 report the histograms of some tests for larger flow rates and specifically for Tests 19, 21, 22, 25 and 30.

These tests were selected with the criterion, on the one hand, of verifying more developed cavitation conditions (Tests 25 and 30) and, on the other, of concentrating on the range of flow rates in which the inception of cavitation seemed to lie (Tests 19, 21 and 22).

Fig. 2. Position A Tests.

Fig. 3. Position B Tests.

Fig. 4. Position C Tests.

Figures 2, 3 and 4 report the frequency (kHz) on the horizontal axis and the noise intensity (dB) on a distinct vertical axis for each of the five above mentioned tests (I – V). At first sight, the experimental tests under the most dangerous conditions for the machinery, that is at the highest flow rates (and highest performance levels), confirmed the sensitivity of the acoustic method in detecting cavitation at its onset. Indeed, the cavitation noise in the high frequency range was detected significantly earlier than the fall in machine performance. In particular, performance was assessed using experimental measures of flow rate and prevalence, which also made it possible to determine the Net Positive Suction Head (NPSH) for each test. The NPSH is defined as the absolute total head, at the center line of the impeller, above the vapour pressure of the fluid and is defined by the equation:

$$NPSH = z + \frac{p}{\gamma} + \frac{V^2}{2g} - \frac{p_v}{\gamma} \quad (2)$$

where z is the height of the intake flange of the machinery in respect to the plane of the impeller and where p , p_v , V , γ and g are respectively the absolute pressure, the vapour pressure, velocity, specific weight of the fluid and acceleration due to gravity.

The NPSH parameter is particularly meaningful as its measurement is typically adopted in technical practice to classify cavitation conditions in cases such as those examined experimentally (in hydro-turbine Net Positive Discharge Head NPDH is typically used) [13]-[16].

However, a more careful comparison of the test results - reported in the histograms in figures 2, 3 and 4 - highlighted a particular utility of the acoustic method, which is not achieved by other methods.

The histograms, which were obtained by moving the microphone to different positions around the machinery during the test, clearly show different frequency peaks (caused by cavitation) in the various positions.

The difference between figures 2, 3 and 4 lies in the fact that the spectral power density histograms for these five tests refer to three different positions (outside the machinery) of the phonometer's detector microphone. In particular, figure 2 refers to acoustic measurements taken in position A indicated in figure 1, while figures 3 and 4 refer to positions B and C indicated again in figure 1.

It should be noted that in order to facilitate the measurement of increases in the diagrams due to cavitation, it is not the real value of the noise intensity expressed in dB that is reported, but rather the difference, again expressed in dB, between the intensity of noise emitted under test conditions and that of the so-called background noise with the same frequency. Identifying the background noise makes it possible to eliminate parasite noise from the measured signal, such as that generated by the surrounding environment and the mechanical noise emitted by the machinery.

In each of figures 2, 3 and 4, Test 19 presents a spectral power density slope that is basically flat, thus indicating the absence of high frequencies that are present in the cavitation phenomenon.

From Test 21 on, it can be increasingly observed that there is a clear rise in the diagrams. While for position A

this increase corresponds above all to the frequency of 6.3 kHz, for positions B and C this rise occurs at frequencies of 16.0 kHz and 9.6 kHz respectively. The marked difference between these three frequencies suggests that there are three different cavitation nuclei. In addition to a first nucleus located near the suction flange (position A), in the position where cavitation is expected to occur, two other unexpected cavitation nuclei were detected. These two nuclei are detected in the pump flow delivery section, in particular in the impeller spiral volute (position B) close to a bleeder orifice fitted on the delivery section of the pump casing (position C).

The acoustic measurements have shown how the design and internal geometry of the machinery affects the fluid flows and can thus facilitate cavitation even in areas where cavitation would not normally be expected [17], [18]. This selectivity, which the other methods cited do not possess and which makes it possible to identify the various nuclei of cavitation in the machinery operating under the same conditions, can be of considerable importance for machinery manufacturers in both the design and the production phases.

4. Conclusion

Cavitation conditions corresponding to higher performance levels are those in which machinery is exposed to the greatest damage. In this field (characterized by high frequencies) the acoustic method shows a particular sensitivity since it is suitable for detecting the phases of cavitation onset. The characteristics of the acoustic method, therefore, are also of particular interest to the managers of working systems. Indeed, the acoustic measurement equipment is non intrusive and last generation technologies make it possible to set up a mobile detection station constituted by a phonometer and a portable and highly sensitive recording device. Such equipment is well-suited for taking measurements in working systems in order to verify whether the working conditions chosen during the management phase can trigger cavitation. Unlike other methods for the direct detection of cavitation, the acoustic method also makes it possible to detect different nuclei of cavitation in the same working conditions. Indeed experimental tests point out that different cavitation nuclei, produced by particular hydrodynamic conditions or by particular internal geometries, have their own characteristic frequency in the spectral power density histogram. The acoustic measurements also show how the design and internal geometry of machinery affects the fluid flows and can thus facilitate cavitation even in areas where cavitation would not normally be expected. This possibility of detecting different cavitation nuclei, under particular flow conditions or particular conformations of machine geometry, can be exploited by manufacturers both for testing prototypes in the design phase and for quality control during the production phase.

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