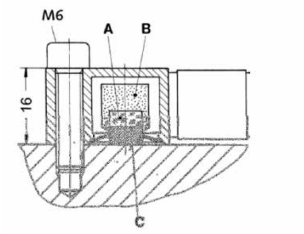
Cavitation monitoring in water turbines using acoustic emission

Acoustic emission measuring chains, sensitive to surface waves between 100 kHz and 900 kHz, are gaining popularity as a modern solution for monitoring highly dynamic events such as cavitation in pumps, turbines and water brakes.

What is acoustic emission?
Acoustic emission (or AE) may be defined as a transient elastic wave generated by the rapid release of energy within a material (source: ASTM E610-82). When a structure is subjected to an external stimulus (a change in pressure, load, or temperature), localized sources trigger the release of energy in the form of stress waves which propagate to the surface. This mostly occurs when a small surface displacement of the material is produced.

Acoustic emission measuring chains are especially suitable for detecting these high-energy surface waves (above 50 kHz) on the surfaces of metallic components, structures or systems. In this respect, they are completely different from accelerometers designed to measure events from 0 Hz to 20 kHz.
An acoustic emission sensor will only be sensitive to high-energy events, and will not see potentially perturbing vibration events (inherent high-pass filtering). For example, an AE sensor can easily detect cracking in a cutting tool without even seeing the vibration of the machine on which the tool is mounted.

Acoustic emission measuring chains
As compared to a typical AE sensor, Kistler's 8152C sensor features a unique mounting and design approach that makes it suitable for higher operating temperatures up to 165 °C, industrial applications and hazardous environments where ATEX/CSA certifications may be required. The 8152C Piezotron AE sensor can be used to measure acoustic emissions from 50 kHz to 900 kHz.



A Ceramic piezoelectric element and impedance converter
B Acoustic backing and internal electronics
C Coupling diaphragm (preloaded by M6 screw 1/4" screw or magnetic mounting

Fig. 1.: Type 8152c acoustic emission sensor, cross section

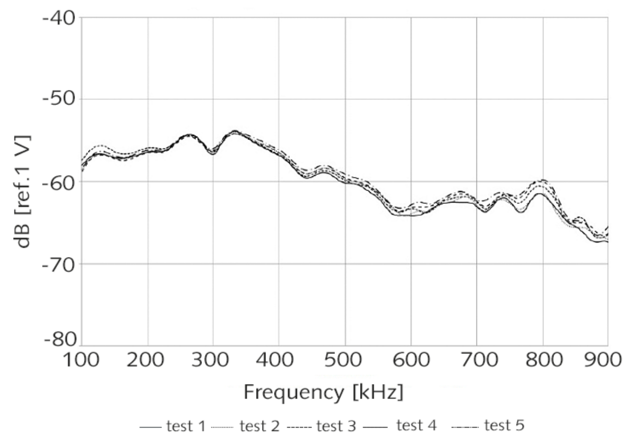


Fig. 2.: Repeatability of measurements tested and remounted using ¼-20 UNF 2A SHCS

The piezoelectric ceramic sensing element is mounted on top of a stainless steel diaphragm which, in turn, is welded to its stainless steel housing (see Figure 1). The diaphragm coupling surface protrudes slightly below the housing and when mounted, provides a well-defined coupling force. This results in reproducible coupling of the sensor to the mounting structure and repeatable measurement results (see Figure 2).

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Due to its design, the sensing element is – to a large extent –acoustically isolated from the housing and is well protected against external noise. An internal impedance converter incorporated into the 8152C AE sensor provides a low-impedance voltage output signal, making it potentially compatible with selected high-speed IEPE data acquisition systems. An internal high-pass filter upstream of the impedance converter provides protection from low-frequency signals and shocks that could either saturate the impedance converter or cause damage to it.

An integral triaxial cable incorporates an outer PFA jacket terminating in a pigtail connection. The AE signal is carried by the signal wire, inner shield and drain wire, which are isolated from the outer shield and housing/diaphragm of the sensor. This provides case isolation from the mounting surface, which is important in some industrial applications. An option that ensures even greater ruggedness is to enclose the same triaxial cable in stainless steel braided armor. In addition, the high- frequency signal content means that a low insertion loss is essential for the cable on an AE sensor; the triaxial cable on the 8152C has a loss of only 2 dB at 900 kHz for a length of 20 meters. Both cable types can be seen in Figure 3.

Fig. 3.: 8152C with integral PFA jacketed cable (left)
8152C with integral stainless steel armored jacket (right)

If an IEPE-compatible data acquisition system (as mentioned above) is not available, the relatively complex high-frequency AE signals must then be processed by the 5125C coupler, as illustrated in the block diagram, Figure 4.

Depending on the expected amplitude of the AE signals, a gain from 1 to 100 in the amplifier stage can be selected.

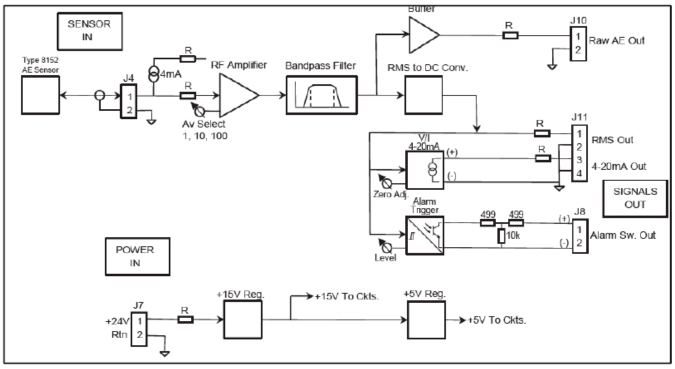

Fig. 4.: AE measuring chain block diagram

A band-pass filter allows processing of the desired frequency range for the AE signal. The right choice of filters (high-pass and low-pass) will affect the signal-to-noise ratio. Typically, AE signals range between 50 kHz and 1 MHz. By determining the characteristic signal frequency, it is possible to set a narrower frequency range that will increase the signal-to-noise ratio and the repeatability of desired signal detection. This output is buffered, and is typically provided either to a data acquisition system for digital signal processing, an oscilloscope or a spectrum analyzer. A digital signal processor may be used for the assessment of filtered AE signals based on statistical methods, amplitude–frequency distribution analysis or violation of any defined thresholds.
Once the signal and its related process events are well known and understood, root mean square (RMS) processing of the signal is commonly performed to allow monitoring of the signal over longer periods of time. RMS evaluation of the signal has become established as an industrial method for describing the intensity of the AE signals in filtered frequency bands. The measurement period can be changed by varying the time constant filter on the RMS-to-DC converter, thus changing the duration taken as the basis for averaging the RMS signal.

$$U_{RMS} = \sqrt{\frac{1}{\tau} \int_0^{\tau} U_{AE}^2 \bullet dt}$$

U_{RMS}: Voltage after RMS converter
U_{AE}: Voltage after filter

Water turbines [1]
A water turbine is a rotary machine that converts the kinetic energy and potential energy of water into mechanical work. Nowadays, water turbines are mainly used in dams to generate electric power. Flowing water applies a force that acts on the blades of a turbine runner. Because the runner is spinning, this force acts over a distance, allowing energy to be transferred from the water flow to the turbine.

What is cavitation and what causes it? [2], [3]
Cavitation is the formation of vapor bubbles in the liquid that flows through any hydraulic turbine. It occurs when the static pressure of the liquid falls below its vapor pressure, and is most likely to occur near the fast-moving blades of the turbines and their exit region.

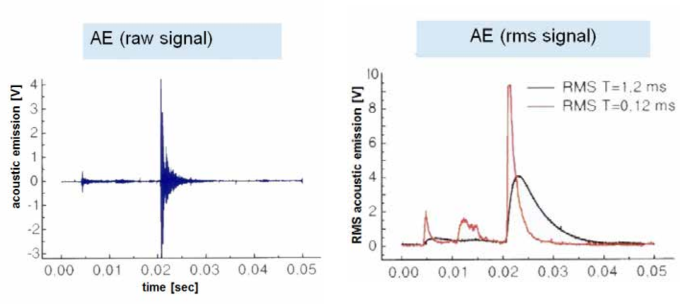

Fig. 5.: Raw AE signal vs RMS AE signal with signal averaging over 1.2 ms and 0.12 ms.

The formation of vapor bubbles in cavitation is not a major problem in itself, but the collapse of these bubbles generates pressure waves which can be of very high frequencies; this can cause damage to the machinery through surface erosion. Smaller bubbles may be more detrimental to the hydraulic machine body without significantly reducing the machine's efficiency. As static pressure decreases further, more bubbles are formed and their size also increases. These

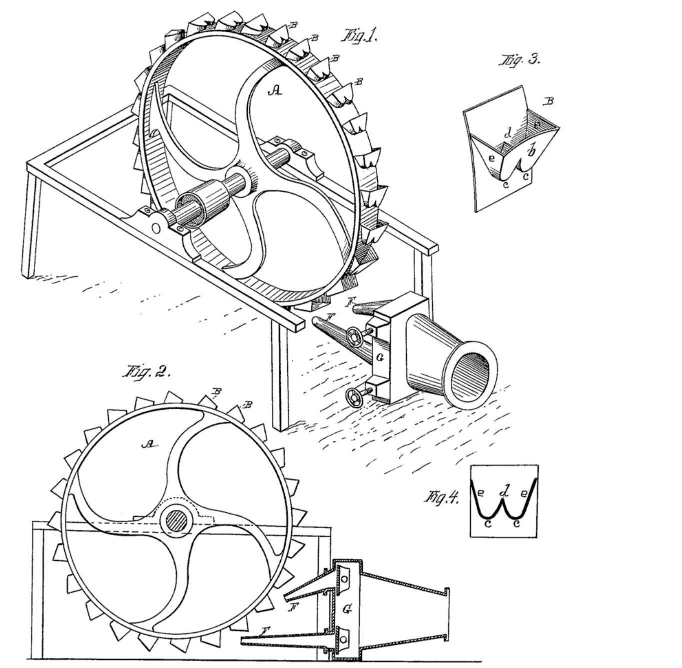

Fig. 6.: Figure from Pelton's original patent (October 1880) Source : L. A. Pelton - US patent 233692, page 1

bubbles coalesce to form larger bubbles and, eventually, pockets of vapor that disturb the liquid flow and cause flow separation, sharply reducing the machine's performance.

Avoiding cavitation [3]

To avoid cavitation while operating hydraulic turbines, the static pressure must be accurately controlled by monitoring several parameters such as the pressure head, flow rate and exit pressure of the liquid. Thresholds can be established using turbine models running in cavitation-free operation mode. Thresholds are then fixed at the level where cavitation starts and efficiency falls.

As already mentioned, undesired cavitation can potentially limit the operational range of hydraulic turbines. It causes noise and vibrations, and can even erode the surface of turbine components. From the economic perspective, however, cavitation-free operation is not the best approach. This makes it essential to achieve a good balance when determining the admissible level of cavitation.

Fig. 7.: Example of cavitation damage. Source : Voith

Using visual observations to gauge the admissible level can give rise to uncertainties. More reliable techniques are now in use, with the help of appropriate monitoring devices. These methods are especially effective during periods of high dynamic activity in the electrical grid combined with ambitious demands on the availability and flexibility of power generation. Techniques of this sort can deliver real economic benefit for the operator. One example of such monitoring systems is the HyCon MD cavitation monitoring module developed by Voith Hydro, based on the measurement of acoustic emissions caused by the cavitation process itself. These acoustic emissions are analyzed in the ultrasonic frequency range, and a characteristic value is derived that can clearly assign the turbine's cavitation state to one of four categories: no cavitation, incipient cavitation, slight (admissible) cavitation or strong cavitation.

The monitoring system consists of a set of 8152C acoustic emission sensors and their 5125C couplers, a high-speed data acquisition and signal processing unit, and an analysis software module. The sensors can be mounted outside the turbine. Based on the measured acoustic emissions and additional machine data such as rotational speed, the software module then calculates the cavitation category for the turbine.

Conclusion

The use of dedicated acoustic emission measuring chains, combined with other parameters such as vibration and rotational speed, makes it possible to optimize the operation of water turbine power plants. This approach also supports flexible revision intervals based on reliable information about the unit's accumulated cavitation "history".

List of references

[1] https://en.wikipedia.org/wiki/Water_turbine

[2] https://en.wikipedia.org/wiki/Cavitation

[3] Cavitation Monitoring in Hydraulic Turbines by Jörg NEcket, Carsten Mende, Emas Taghi Zoghi, Voith Hydro Holding GmbH &Co

Kistler Group
Eulachstrasse 22
8408 Winterthur
Switzerland
Tel. +41 52 224 11 11