Influence of the vibro-acoustic sensor position on cavitation detection in a Kaplan turbine

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Abstract. Hydraulic turbines can be operated close to the limits of the operating range to meet the demand of the grid. When operated close to the limits, the risk increases that cavitation phenomena may occur at the runner and / or at the guide vanes of the turbine. Cavitation in a hydraulic turbine can cause material erosion on the runner and other turbine parts and reduce the durability of the machine leading to required outage time and related repair costs. Therefore it is important to get reliable information about the appearance of cavitation during prototype operation. In this experimental investigation the high frequency acoustic emissions and vibrations were measured at 20 operating points with different cavitation behaviour at different positions in a large prototype Kaplan turbine. The main goal was a comparison of the measured signals at different sensor positions to identify the sensitivity of the location for cavitation detection. The measured signals were analysed statistically and specific values were derived. Based on the measured signals, it is possible to confirm the cavitation limit of the examined turbine. The result of the investigation shows that the position of the sensors has a significant influence on the detection of cavitation.

1. Introduction

When hydraulic turbines are operated at off design conditions, cavitation may occur at the runner and guide vanes. Depending on type and degree of the cavitation, parts of the turbine may be damaged or in severe cases destroyed. Incipient cavitation is a state where first traces of visually observable cavitation bubbles occur. Admissible cavitation, in contrary to fully developed cavitation, is not erosive and has no potential to damage the turbine yet. Therefore it is important to get knowledge about the occurrence and state of cavitation in hydraulic turbines.

Especially when the turbine is operated close to the manufacturer’s defined cavitation limit, which is based on model tests, admissible cavitation is existent. During the cavitation process high frequency acoustic emissions caused by the implosion of the bubbles occur. These emissions can be detected with piezoelectric acoustic emissions sensors (AE sensors). Cavitation in hydraulic machines causes also lower frequency vibrations [1], which can be measured with accelerometers.

Cavitation detection in turbines has been investigated in the literature and it is still in focus of researchers in order to understand the complex mechanisms of cavitation and to find means to avoid...
the damage caused by cavitation erosion. Visual detection at prototype ship propellers [2] and hydraulic turbines [3] are difficult due to limited optical accessibility and insufficient illumination. Model tests based on visual cavitation detection and the efficiency drop are usually carried out before delivering a new prototype machine, so these methods are well tested. Cavitation detection at model tests based on acoustic emissions, vibrations and optical methods in model turbines are state of the art, [1], [3], [4], [5], [6], [8]. Measurements on prototype turbines have been carried out, e.g. [1], [7], [8].

The goal of the present experimental investigation is the detection of cavitation based on the acoustic emissions and vibrations in a prototype Kaplan turbine, which does not suffer from distinct erosive cavitation within its continuous operational range. Operating points beyond the continuous operational range with fully developed cavitation were reached by exceeding the manufacturer’s cavitation limit. Besides the detection of incipient cavitation, states of cavitation with higher damaging potential were investigated, too. The main goal of the investigation is to analyse the behaviour of the measured signals beyond the admissible cavitation limit at different sensor positions.

2. Test case – Prototype Turbine
To get the acoustic emissions (AE) and vibration data for the analysis, one large Kaplan turbine at the power plant Wallsee-Mitterkirchen at the Danube River in Austria was equipped with a data acquisition system to record the emitted acoustic signals and vibrations during operation. The diameter of the runner is 7.8 m and the runner has four blades. The distributor has 24 guide vanes and the semi spiral case contains twelve stay vanes.

For the measurement the turbine was operated manually with temporarily switched off operation range limits to enable the investigation of more severe cavitation conditions, too. Beginning at a part load, twenty operating points with almost constant head and increasing discharge are investigated up to the maximum discharge of the turbine. Thereby seven operating points were located above the admissible cavitation limit which is known from model tests. During the investigation the variation of the head referred to the average head was within 1.7 % being considered as a “constant head” condition. In this way, acoustic and vibration signals at different positions at the turbine in cavitation free and cavitating operating points were obtained for analysis.

3. Experimental set up
The turbine was equipped with three AE-sensors to measure the acoustic signals during operation. The used sensors are piezoelectric wideband acoustic sensors with an external amplifier. Two AE-sensors have a frequency range of $f = 100 \text{ kHz}$ to $1 \text{ MHz}$ and a typical maximal sensitivity of -65 dB ref 1V/$\mu$Bar. The third AE-sensor has a frequency range of $f = 100 \text{ kHz}$ to $900 \text{ kHz}$ and a typical sensitivity of 48 dB ref 1V/(m/s). All AE-sensors were equipped with a 100 kHz high pass filter. One sensor was mounted at the inner cover above the runner. The second sensor was located at the upper cover behind the guide vanes. These two sensors were glued to the machine surface with the silicone adhesive and secured with a spring pre-loaded magnetic clamp (figure 1 and 2). One accelerometer was bolted on a sheet glued to the machine surface above the AE-sensor at the inner cover (figure 1 (a)). The second accelerometer was bolted to a cube, which was glued on the axis of a guide vane (figure 3). Both accelerometers have a linear frequency range from $f = 0.4 \text{ Hz}$ to $14 \text{ kHz}$ and a typical sensitivity of 100 ±5 % mV/g.
The angular position of the sensors at the upper and lower cover and the guide vane was 180° to the direction of the head water. The third AE-sensor was located at the discharge ring. It was bolted to a non-corrosive sheet which was glued to the surface of the discharge ring with a two component adhesive (figure 4). The schematic position of the sensors is shown in figure 5.
The data from the sensors were recorded with a high speed data acquisition card for the AE-sensors and a data acquisition card for ICP accelerometers. The signals from the AE-sensors were recorded with a sampling rate of 4 MS/s and the vibration signals were sampled with 50 kS/s. The duration of one measurement was $t = 0.92$ s which corresponds to one revolution of the runner. For each operating point two measurements were done successively. All measurements were triggered by an inductive switch located at the turbine shaft. The operating data were simultaneously obtained and recorded from the power plant control system.

4. Analysis of the measured signals

Two characteristic values were derived from the recorded raw data in order to get information about the acoustic and vibration level at different positions at the turbine at the examined operating points. In addition, the time series of the recorded acoustic emissions were examined for characteristic patterns. Assuming that the frequency range directly related to cavitation lies mainly above 100 kHz, the focus of the analysis is based on the acoustic emissions data. The acoustic emissions signals are characterized by bursts of short peaks of high amplitude when cavitation occurs. With increasing cavitation intensity the amplitudes of the peaks increase. Increasing vibration level of the turbine is often related to the occurrence of cavitation. Therefore the root mean square value (RMS) was derived from the measured acoustic and vibration signals. It is defined as:

$$\Psi_x = \sqrt{\frac{1}{n} \sum_{t=0}^{n-1} |x_t|^2}$$

where $\Psi_x$ is the RMS value and $n$ is the number of samples of the time series $x$.

The number of signal peaks with high amplitude increases with increasing cavitation intensity resulting in an increase of the defined RMS-value. To benefit from this correlation a second characteristic value is applied in this analysis, which counts the events exceeding a set threshold. An event is counted as a positive value of the time series when the trend of the values exceeds and falls back below a defined threshold. In this analysis only the positive values of the time series are used, because it is assumed that the signal is symmetric against the zero level.

These characteristic values were adopted on the time series of the acoustic emissions and the vibrations signals. As the signal value at the different examined sensor positions were different, different threshold values were set. The threshold for the different sensors and positions was determined at the part load operating point with the lowest discharge. The limit was set to a signal value above the main signal noise with only few peaks above the threshold level. The set threshold values are outlined in table 1. The counter values were scaled to one second measurement duration and denoted as E/s (events per second).

| sensor       | position     | value    |
|--------------|--------------|----------|
| AE-sensor    | inner cover  | 0.3 V    |
|              | upper cover  | 0.3 V    |
|              | discharge ring | 3 V     |
| accelerometer| inner cover  | 20 m/s²  |
|              | guide vane   | 2 m/s²   |

Table 1. Set threshold values for the different sensor positions
For each examined operating point two RMS and two E/s values for each sensor position were obtained. As the head was constant, the operating points are characterized by the discharge. The admissible cavitation limit for the head during the measurement is known. Thus, the discharge of each operating point is normalized with the discharge of the operating point at the admissible cavitation limit.

5. Results of the experimental investigation
In order to get information about the suitability of the sensor position and the influence on the measured acoustic emissions, the time series and the characteristic curves of the RMS and E/s values of the different sensors and sensor positions are compared.

5.1. Time series of the acoustic emissions
The time series of one machine revolution gives information about signal level at different operating points and patterns related to turbine parameters such as the number of runner blades or number of guide vanes. Figures 6 and 7 show exemplarily the time series measured at the inner cover in an operating point at part load and at maximum discharge. The signal at part load is characterized by a constant noise and a few bursts of signal peaks. At t = 0.22 s a distinct burst with high amplitude indicates a cavitation event. This time series is used to determine the threshold levels for the E/s analysis at the inner and the upper cover. The time series of the operating point at maximum discharge show several bursts with high amplitudes. The distribution of the bursts with high density corresponds to the blade number and the number of the guide vanes.

Figure 6. Time series of the acoustic emissions measured at the inner cover at part load.

Figure 7. Time series of the acoustic emissions measured at the inner cover at maximum discharge.

5.2. RMS and E/s of the measured acoustic emissions and vibrations
Figure 8 shows the RMS values of the acoustic emissions at the examined positions versus the normalized discharge. The cavitation limit for the present head is reached at $Q/Q_{\text{cav}} = 1$. The RMS-values of the acoustic emissions at the inner and upper cover have a low value and flat shape up to $Q/Q_{\text{cav}} \approx 0.8$ followed by an increase until the cavitation limit. Above the cavitation limit, the trend of the RMS-values becomes fluctuating which indicates a more transient appearance of acoustic emissions. This phenomenon could be related to the transient behaviour of cloud generating cavitation. In general the RMS values at the inner cover are constantly higher than at the upper cover.
The RMS-values of the acoustic emissions measured at the discharge ring have higher magnitudes but there is only a small increase up to the cavitation limit visible which is followed by a decrease. The fluctuating trend observed at the inner and upper cover above the cavitation limit is more distinct at the discharge ring at lower discharges. This flat trend and high value of the acoustic emissions indicate gap cavitation, which is often present over a wide operating range in Kaplan turbines. The sensor position at the discharge ring has the closest position to the occurring gap cavitation between the runner and discharge ring which results in a high signal level.

The distribution of the E/s-values of the acoustic emissions shows the same trend like the RMS-values (figure 9). The increase of the values at the inner and upper cover has a steeper gradient compared to the RMS-values. The fluctuations of the values at operating points with higher discharge than 0.97 of the cavitation limit discharge are more distinct and have a higher range. At low discharge the E/s-values at the inner and upper cover are very similar but above Q/Q_{cav} = 0.8 the E/s-values at the inner cover have a higher level.
The $E/s$-values of the acoustic emissions measured at the discharge ring has a small increase followed by a decrease at the cavitation limit (figure 9). The fluctuations are analogue to the RMS-values at this sensor position and indicate a high acoustic level.

The RMS-values derived from the vibration signals at the inner cover and at the guide vane (see figure 10) show a resemblance to the RMS-values of the acoustic emissions up to the cavitation limit. Above the cavitation limit the trend is in average almost constant at the inner cover and decreases at the guide vane to values which correspond to discharges below the cavitation level. The RMS-values at the guide vanes are constantly above the level determined at the inner cover. Fluctuations of the values above the cavitation limit are also visible. Figure 11 shows the $E/s$-values of the vibration signals. The $E/S$-values of the vibrations at the inner cover have higher values around the cavitation limit. At higher discharge, the characteristic of both curves decreases to values below the cavitation limit. Due to the stagnation and decrease of both characteristic values derived from the vibrations at both examined sensor positions, a clear statement based on the magnitude of the characteristic values is not possible.

Figure 10. RMS characteristics at the two sensor positions

Figure 11. $E/s$ characteristics at the two sensor positions (threshold: cover, guide vane: $20 \text{ m/s}^2$)
5.3. *Time series of the acoustic signals at different sensor positions*

The figures 12 and 13 show the time series of the acoustic emissions measured at the discharge ring at part load and at maximum discharge. In both operating points the blade number of the runner is present with several bursts per runner blade. At the part load operating point two to three bursts can be observed. Beside the bursts on the runner blades at maximum discharge, numerous bursts between the runner blades with smaller amplitudes are observed. This indicates multiple cavitation structures at the four runner blades and an interaction between the runner and the guide vanes regarding the measured acoustic emissions. At this discharge the guide vanes overhang the guide vane bottom ring and therefore are supposed to have detachments or cavitating vortices which interact with the runner blades.

The amplitude of the signal peaks in both operating points is comparable. This is in accordance with the characteristic values at this sensor position, which also have no significant differences in magnitude (see figures 8 and 9).

![Figure 12](image1.png)  
**Figure 12.** Time series of the acoustic emissions measured at the discharge ring at part load.

![Figure 13](image2.png)  
**Figure 13.** Time series of the acoustic emissions measured at the discharge ring at maximum discharge.

5.4. *Conclusions*

A cavitation measurement based on acoustic emissions and vibrations was carried out on a large Kaplan turbine. The signals were measured at different sensor positions and at different operating points. The characteristic values derived from the measured signals show a dependency from the sensor location. The acoustic sensor position at the inner cover and the upper cover show a similar trend with increasing discharge. Both characteristic values have an increasing magnitude and when the admissible cavitation limit is exceeded, significant fluctuations appear. Both sensor positions are suitable for cavitation detection based on the acoustic emissions. The sensor position at the discharge ring is not suitable for cavitation detection, because the measured signals and the derived characteristic values do not change significantly above the admissible cavitation limit.

The trend of the characteristic values derived from the measured vibration signals shows a good similarity at discharges up to the cavitation limit close to Q/Q\text{cav} =1. For higher discharge both characteristic values, RMS and E/s, decrease instead of further increase. Thus, the vibration signals at the examined positions are only suitable to detect the cavitation limit in this turbine. Beyond the admissible cavitation limit the vibration signals at the examined positions are not reliable for the applied analysis method. This is caused by the ambiguity of the derived characteristic values for further increased discharge rates. One possible reason for this behaviour could be a higher damping of measured signal by the vapour filled cavitation structures.
Regarding the time series of the acoustic emissions signals, the interaction between the runner and the wicket gates is visible. At high wicket gate openings the pitch of the guide vanes are visible in the time series. The overhanging guide vanes at high discharge affect the cavitation on the runner blades.

In this experimental investigation the known cavitation limit was confirmed with the acoustic emissions above a frequency of $f = 100$ kHz measured at the inner and upper cover of the examined vertical Kaplan turbine.

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