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Cavitation Monitoring in Hydraulic Turbines

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1. Introduction

Cavitation, evaporation and condensation of water due to pressure changes, in hydraulic turbines may occur. It typically causes noise, vibration and – finally – limits the operating range of the turbine. If cavitation is present over a long period of time or with a high intensity, the surface of turbine components can even become eroded. This usually deteriorates the efficiency and, at the end, causes downtime of the unit due to repair work.

During prototype operation it is difficult to get instantaneous and reliable feedback on the cavitation state of the turbine. The visual access during operation is poor and only indirect and fuzzy conclusions can be drawn when visual inspection of the state of the turbine is possible during a maintenance downtime. Beside the costs for the downtime, this indirect approach does not allow to minimize cavitation occurrence in the machine during flexible operation. Due to the requirement of the grid, this becomes more and more important and beneficial for the owner. A method to detect cavitation, especially erosive cavitation, during operation would pave the way for a maximization of the turbine output without harming the blades as well as it would give input for flexible revision intervals.

Many authors studied the vibration emissions of cavitation in different frequency ranges extensively in time and frequency domain. Cavitation estimators and prediction models for examined test cases were derived, e.g. [1], [2], [3], [4], [5], [6], [7], [8], [9]. Amplitude modulations and modulations of the characteristic frequencies indicate cavitation at the examined test cases. Gruber et al applied an active ultra-sonic system in combination with machine learning methods to distinguish different cavitation phenomena [10]. Cavitation tests on a prototype turbine showed an ambiguity of the analysed vibration signals which indicates a dependence of the vibrations on the examined test case [11]. Thus, the application of vibration signals for a universal cavitation estimator is hazardous as a unique statement might not be obtained.

By analysing the noise of the cavitation, an online monitoring system to assess the cavitation state of the turbine is presented in this paper. A calibration-free real time method to analyse the acoustic emissions in a cavitating turbine is shortly described. More details can be found in [12]. The developed method works without prior knowledge of the machine, i.e. the installation process is fast and is the same for different machines. The monitoring system can deliver immediate feedback – no cavitation, incipient cavitation, strong cavitation and severe cavitation – as well as long-term evaluation by recording the cavitation indicator over time. This allows assessing the load on the blade by cavitation and, therefore, gives important input on a flexible maintenance plan.

In this paper the analysis procedure of the sensor signals and examples of validation test cases are presented. The outlook sketches the possible gain for the operator and explains the benefit in more detail.

2. Analysis method

The used analysis method is based on acoustic emissions acquired by a piezo electric broad band sensor over one or more machine revolutions. It is based on the ultrasonic acoustic emissions above frequencies of 100 kHz.

The time signals of the acoustic emissions sensor during cavitation are characterized by sharp bursts. A de-noised signal of the acoustic emissions recorded for five revolutions at the upper head cover of a prototype pump turbine under cavitation condition is exemplarily shown in figure 1.

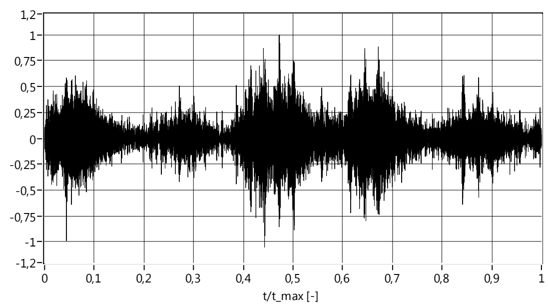

Fig. 1. De-noised signal in time domain

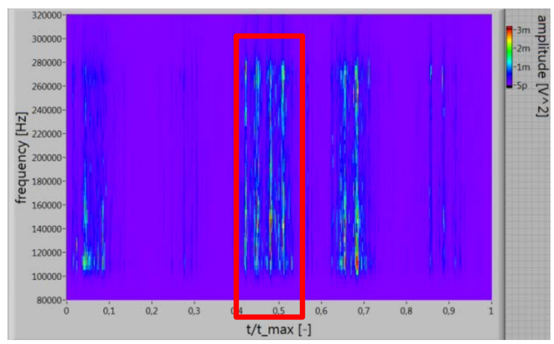

Fig. 2. Corresponding spectrogram

Several sharp signal amplitudes are visible. The source of these signal bursts are cavitating runner blades, as leading edge cavitation is expected in the shown operating point.

In the frequency domain cavitation is characterized by a distinct increase of signal power. Figure 2 shows the spectrogram corresponding to the time series of data presented in figure 1. The cavitating runner blades cause a high signal power in the frequency band between f = 100 kHz and f = 280 kHz. In the marked time range four successive cavitating runner blades are clearly observable.

For the automated cavitation diagnosis, the time series of each machine revolution is divided into segments. For each segment the power spectrum of the time series is calculated for frequencies above f = 100 kHz. All of the resulting power spectra for a prototype pump turbine in three operating conditions are shown in figure 3. The conditions are: part load without cavitation (left), cavitation limit (middle) and above the admissible cavitation limit (right).

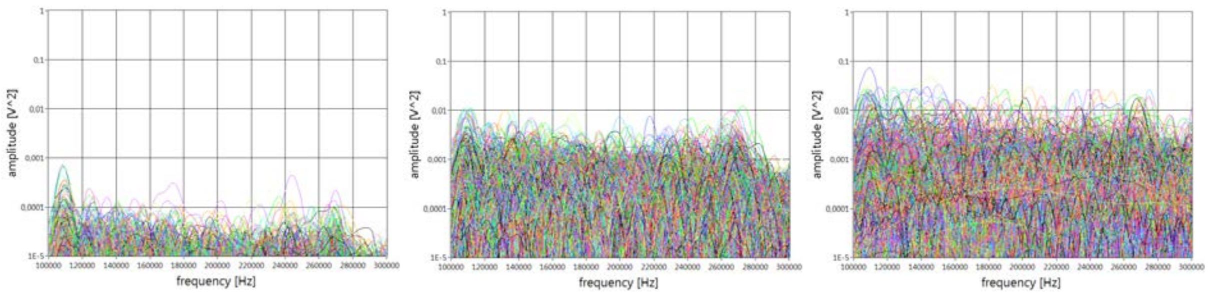

Fig. 3. Power spectra of the signal segments of a prototype pump turbine

From these power spectra, a characteristic value is derived. The number of oversteppings of the amplitudes in the power spectrum over an empirical threshold value is counted for every power spectra of one machine revolution. The characteristic value K is derived from this counter. It is characterized by a steep increase when cavitation occurs making the evaluation method widely independent of the empirical threshold value introduced above. To distinguish between several states of cavitation, three of these characteristic values are derived in the analysis. Thus, three characteristic values K1, K2 and K3 are calculated for each analysis loop and, consequently, four states of cavitation can be determined. The time-averaged state of cavitation is displayed on the user interface with a signal light. The four displayed states of cavitation are listed in Table 1. Both, the determined state of cavitation of each analysed machine revolution and the averaged indicator are stored and are available for archiving and long term analysis.

Table 1: Chosen signal light colours as function of cavitation states

signal light	**state of cavitation**
green	“no cavitation”
yellow	“incipient cavitation” (i.e. admitted cavitation)
orange	“cavitation” (above cavitation limit)
red	Severe cavitation

3. Test cases

1.1. Model turbine

The acoustic emissions were recorded at the discharge ring of an axial model turbine with a runner diameter of D = 0.34 m. Different operating points without and with cavitation were examined. A stroboscopic light was installed at the discharge ring to capture the cavitation structures at the adjusted operating points.

Two operating points with different cavitation behaviour are exemplarily presented. Figure 4 shows the runner blade without cavitation (left) and severe cavitation (right).

The pictures are marked with the determined state of cavitation. As can be seen from the figures, the analysis method estimates the state of cavitation of the runner blades correctly without additional calibration.

Fig. 4. Operating points without cavitation (left side) and strong cavitation (right side)

1.2. Prototype turbine

The analysis method was also tested with the acoustic emissions recorded at a prototype Kaplan turbine at a power plant located on the Danube River. The turbine has four blades and a diameter of D = 7.8 m. The rotational speed of the turbine is n = 65.2 rpm. The turbine was operated manually for the measurements to enable operation points above the cavitation limit. The head variation during the measurement was small (+/- 0.8 %). Different operating points from part load with no cavitation up to the maximum discharge of the turbine were investigated. The admissible cavitation limit of the turbine is known from documented cavitation observations during model tests.

The obtained results of the presented analysis method are shown in table 2. The operating points are characterized by the normalized machine discharge. The admissible cavitation limit, is at Q/Q_{rated} = 0.93.

Table 2: Detected states of cavitation in a Kaplan prototype runner

State of cavitation						CL*)		
Q/Q_{rated} [-]	0.54	0.59	0.67	0.87	0.90	0.93	0.97	0.99

**) CL = "Cavitation limit derived from model test"*

At Q/Q_{rated} = 0.54 admissible cavitation is detected. Cavitation at the gap between discharge ring and runner blade at part load is the identified reason from model tests. Between Q/Q_{rated} = 0.59 and 0.87 no cavitation is detected as expected. At the operating points with Q/Q_{rated} = 0.90 to 0.93, the latter is the known cavitation limit, admissible cavitation is detected. Above Q/Q_{rated} = 0.97 cavitation and severe cavitation is detected. The change from “admissible cavitation” to “cavitation” confirms the known cavitation limit

4. Comparison and further applications

A comparison with the widely used analysis methods, e.g. described in [7], is done using the same data sets. The results of both are displayed in figure 5. The analysis methods used previously are based on the evaluation of the RMS-value of the time series and an event counter E/s. A threshold for the event counter is set to a cavitation-free reference operation regime of the examined turbine. As the available data sets comprise two machine revolutions, two RMS-values and E/s-values are plotted for each examined operating point. On the left-hand diagram of figure 5, the black curve is the development of the event counter E/s for the first measured machine revolution at the examined operating point while the blue curve represents the second machine revolution. Analogous to the E/s-value two RMS-values are plotted for one examined operating point. The cavitation limit is marked with a hatched area. The determined state of cavitation of the new analysis method is characterized by the coloured area of the chart and corresponds to the values of table 2.

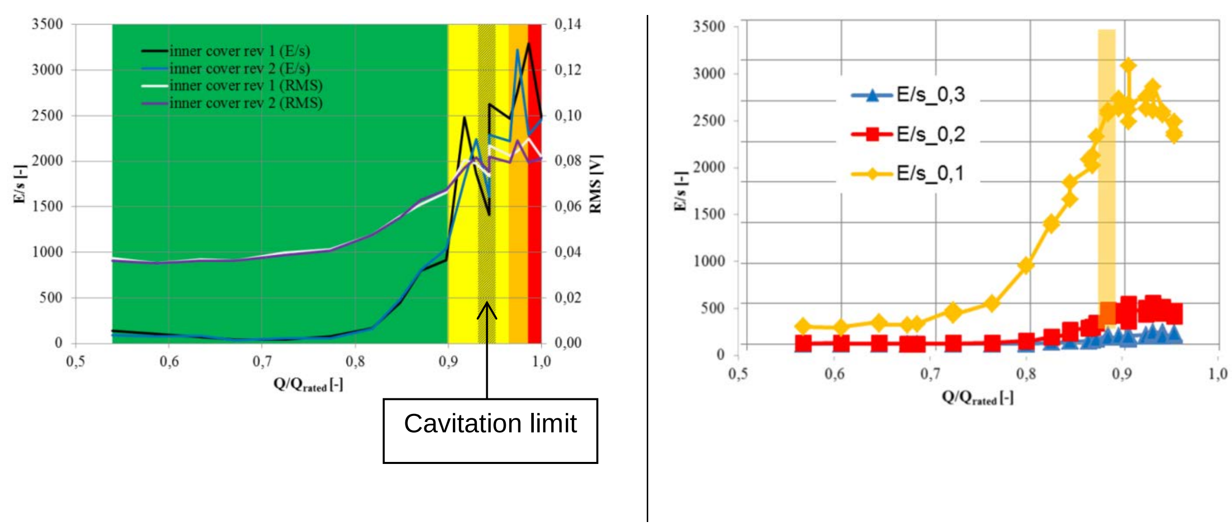

Fig. 5. Left: Results of the new and previously used analysis methods

Right: influence of threshold value on E/s (thresholds 0.1, 0.2, 0.3

For flow rates larger than Q/Q_{rated} = 0.9 the RMS-values and especially the E/s-values begin to fluctuate. The distinctiveness, particularly of the RMS-values above the cavitation limit, is relatively low. The curves of the first and second revolution differ obviously. In combination with the large dependency on the threshold value itself – as it can be seen on the right hand side - this makes it difficult to define a sharp cavitation criterion without prior knowledge – i.e. calibration of the machine. The newly developed evaluation is more robust due to the steep gradient of the calculated characteristic values, i.e. no prior knowledge of the machine is needed.

To verify the derived analysis method regarding its universal application, several prototype and model test cases were examined to check the response of the characteristic values and the correct determination of cavitation. The defined threshold values for the calculation of the characteristic values were identical for all examined test cases. No individual calibration was made and, thus, calibration is deemed to be unnecessary.

Two different model pump turbines and two different model bulb turbines were examined. The characteristic values increased with increasing cavitation and the determined state of cavitation was plausible and corresponded to the visual observations and the evaluation of the observed cavitation structures.

The verification of the analysis method at different prototype turbines showed good and very reasonable results. Besides the presented prototype Kaplan turbine the method was tested on Francis turbines, on pump turbines, on a propeller turbine and on a Voith StreamDiver®. The known cavitation limits at different operating regimes were confirmed. Cavitation detection at operating conditions at part load was also plausible.

5. Available Monitoring System

The developed monitoring system consists of a set of robust high-frequency sensors and amplifiers, a high-speed data acquisition and signal processing unit as well as an analysis software module. The sensors can be attached outside the turbine. Based on the measured acoustic emissions and additional machine data like rotational speed the software module calculates the above mentioned characteristic value and can provide the cavitation state of the machine during operation.

Two valuable scenarios for the operator are currently supported:

- Short period measurement campaign to investigate operation schemes of interest (e.g. after rehabilitation without model tests, known cavitation problems, special operation conditions)
- Support the establishment of flexible revision intervals based on reliable information on the accumulated cavitation "history" of the unit. For this purpose a variety of online monitoring and archiving functions are available. The benefits for the operator are obvious:
    - The revisions can be planed more individually. This avoids unnecessary downtimes of the units.
    - The revisions can be planed more effectively. The amount of welding material as well as the needed capacity can be prepared and will contribute to a shorter downtime.

  Both aspects sum up to more availability and, thus, result in a larger profit.

More information on the system can be found in [13].

6. Conclusions and Outlook

The derived analysis method presented here shows encouraging results of cavitation assessment for the examined test cases. The onset of cavitation can be identified and different cavitation levels are detected. The main advantage compared to well-known analysis methods based on e.g. the RMS-value or an event counter in the time domain is that individual calibration for each test case is unnecessary. This opens up the path to flexible maintenance periods. Both, long-term and short-term observations are possible, each giving important insights into the machine behaviour and directions for the operation of the machine. The instantaneous or short-term feedback can be used for an optimization of the operating range while a long-term analysing of the signal can be used for an individual, machine dependent adjustment of the revision intervals.

A major benefit for the operator is the better planning of revision intervals as well as a higher availability.

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