Cavitation measurements on a pump-turbine model

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Abstract. When a hydraulic turbine is operated at off-design conditions, cavitation on the runner and other machine parts can occur. Vibration, noise and erosion caused by cavitation can damage the turbine and lead to a limitation of the operational range. To avoid damage of the turbine, it is fundamental to get knowledge of the presence of cavitation. In this paper, the acoustic emissions at a pump-turbine model at different operating conditions with and without the presence of cavitation were recorded and analysed. High speed video recordings were carried out simultaneously to validate the acoustic measurements. The main goal of the investigation was to compare the acoustic emissions with the visual observations at operating conditions with cavitation on the leading edge of the turbine runner. The analysis of the recorded signals and the visual observations are in good accordance for the investigated operating points.

1. Introduction

Cavitation at the runner and guide vanes can occur when a turbine is operated at off design conditions. If cavitation gets fully developed, parts of the turbine are prone to erosion damage. The turbine manufacturer permits an incipient state of cavitation, which is observed and evaluated during model tests and is which is supposed to be not erosive. Cavitation detection in model turbines based on acoustic emissions, vibrations and optical methods are state of the art [1] [2] [3] [4] [5]. When cavitation is measured in a model turbine by a physical quantity like acoustic emissions, it is important to get knowledge about the occurrence and state of cavitation visually. Unlike in prototype turbines the visual accessibility is widely possible in axial model turbines [1] [2] [3]. In radial model turbines the view onto the leading edge is hindered due to limited illumination and the design of the runner but observation through the transparent draft tube cone onto the runner outlet is a current method [4][5].

In this paper the acoustic measurement of the pressure side leading edge cavitation at a model pump-turbine with the visual evaluation via high speed video recording is presented. Therefore a window and an illumination system were installed in the lower wicked gate ring. Several operating conditions with different states of cavitation were measured and high speed video recordings were captured. The goal of the present experimental investigation is the detection of cavitation at the leading edge based on the acoustic emissions and get knowledge of the relation between measured signals and visual observations.

2. Experimental setup

The measurements were carried out at the closed loop test rig (fig. 1) at the Institute of Fluid Mechanics and Hydraulic Machinery, University of Stuttgart. The investigated pump-turbine model
was equipped with an acoustic emission sensor (AE-sensor). The sensor was installed at the upper cover. The position on the upper cover was chosen to get as close as possible to the cavitation structures on the leading edge of the runner. The sensor was glued directly to the machine surface.

![Figure 1. Closed loop test rig.](image1)

![Figure 2. Acoustic emission sensor on upper cover (left) and cross section of the pump-turbine model (right).](image2)

Figure 2 shows the installed acoustic emissions sensor. The measured signals are filtered, amplified and recorded by a data acquisition system with a sampling rate of 6 MS/s.

To get visual access to the leading edge of the runner in turbine mode, observation windows and illumination were installed in the lower distributor ring of the pump-turbine model. The window with a diameter of 30 mm permits the view on the leading edge using a high speed camera. To obtain sufficient illumination for high speed recording, four high power light emitting diodes with a maximum output of 1665 lumens were installed in milled-out portions beside the window. Figure 3 shows the modifications of the lower distributor ring viewed from the runner-side. The high speed video records were captured with 6500 fps and analyzed by rating the extent of the visible cavitation structures.

![Figure 3. Observation window and illumination](image3)

3. Measurement

To induce cavitation at the leading edge of the runner, one operating point at low head was adjusted for the measurement. For the examined operating point the specific flow $Q_1'$ was 83% of $Q_{1' \text{BEP}}$ and the specific speed $n_1'$ was 132% of $n_{1' \text{BEP}}$. The head, discharge and machine speed were kept constant and the cavitation number $\sigma$ was gradually lowered by lowering the system pressure of the closed loop test rig to obtain operating conditions with increasing cavitation. The cavitation number $\sigma$ was constant during the measurement of one operating point. The measurement and the high-speed video were synchronously triggered by a key-phaser located on the machine shaft.

4. Analysis of the measured signals

The acoustic emissions caused by cavitation are broadband signals reaching the ultrasonic range. To avoid mechanical background noise from the turbine, the analysis of the signals was focused on the frequency range above $f = 100$ kHz. The signals were conditioned and wavelet-denoised. The time series at each $\sigma$-value were divided into several sections over one machine revolution to get an angular resolution and the power spectrum was calculated for each section. As cavitation sets in, the distribution of the power spectrum in the analysed frequency range is characterised by a distinct
increase. By summing up, normalising and weighting the signal power amplitudes exceeding a set threshold in the frequency domain, characteristic values were derived to characterise the cavitation state of the turbine runner. A detailed description of the method can be found in [6].

The development of the characteristic curve for the threshold value at the examined sensor position is plotted versus the cavitation number, see figure 4. The development shows a nonuniform increase with a significant step around $\sigma = 0.4$. Four of the examined operating conditions, numbered 0 to 3, are exemplarily presented.

Figure 4. Development of characteristic value

Figure 5 shows a reference picture at $\sigma = 1.06$ without cavitation. The viewing perspective is upwards from the lower wicket gate ring on the guide vane and leading edge of the runner towards the turbine head cover. At operating condition 1 first cavitation structures at the leading edge are visible (fig. 6). Not all runner blades are affected, which is referred to the inequality of the leading edges of the runner blades.

Figure 5. Operating condition 0, no cavitation.  

Figure 6. Operating condition 1

Figure 7. Operating condition 2

Figure 8. Operating condition 3
Operating condition 2 (fig. 7) is characterised by distinct cavitation structures at the leading edge but not all runner blades are affected over one revolution. Further a fluctuation of the volume of the cavitation structures while passing the guide vane is observed. This indicates a changing pressure field at the runner leading edge caused by an interaction of runner and guide vanes. At operating condition 3, severe cavitation is visible with large detaching structures on all runner blades (fig. 8).

Regarding the occurrence and extent of the observed cavitation structures, a correlation to the development of the characteristic curve determined from the acoustic emissions can be found. At the operating condition 0 cavitation was neither detected with the analysis of the recorded acoustic emissions signals nor visually. The appearance of sporadic cavitation structures lead to an increase of the characteristic value. The step in the development of the characteristic value correlates with the observation that all runner blades are affected by cavitation.

5. Results and Conclusions
The comparison of a characteristic value derived from measured acoustic emissions and the visual observations at operating points with pressure side leading edge cavitation show a good accordance at the examined operating points. The observed increase of the extent of the cavitation structures by lowering the cavitation number corresponds to the increase of the characteristic value. The results of the presented investigation show, that the analysis of acoustic emissions is an appropriate method to detect leading edge cavitation in the presented pump-turbine model. The visual access to the leading edge of the runner facilitates the matching of a cavitation indicator based on measured quantities.

6. Outlook
The purpose of the investigation presented here is to validate the results of the analysis of the acoustic emissions signals for cavitation detection at the leading edge of a radial runner. The results provide contribution in the development of a universal cavitation monitoring system. The next steps to be done are the analysis and validation of different operating points and compare the results with the analysis of axial model turbines and prototype turbines.

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