Experimental research on pressure fluctuation characteristics of high-head Francis turbine under part load conditions

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Abstract: Pressure fluctuation at partial load operation is an obvious and harmful phenomena in Francis turbines. It could be induced by rotor stator interaction and cavitation vortex rope in draft tube and must be minimized during the design of Francis turbine. To reduce the pressure fluctuation at partial load operation, accurate assessment of the cause of this phenomena is crucial. In this paper, a reduced-scale physical model of a high head Francis turbine is used as the research object, and the test technique is applied to investigate the excitation source of the pressure fluctuation at two partial load operation conditions. Based on experimental data, it can be concluded that the amplitude of pressure fluctuation in the draft tube significant is increased with the decrease of the power of turbine, which is indicated that the stability of turbine deteriorated sharply with the power reduced. But the dominant frequency of the pressure fluctuation is almost the same. And the strong pressure fluctuation in the draft tube can be transmitted to the upstream components, which are affected the pressure fluctuation caused by rotor stator interaction.

1. Introduction
With the continuous depletion of fossil energy, the ever escalating renewable energy demand has promoted the generation of hydropower towards a high efficiency and more flexible system that can operate in wider working region. To ensure the stable operation of hydropower plant, the hydropower turbines are required to handle the instable phenomenon such as cavitation, pressure fluctuations and rotor-stator interactions effectively. Francis turbine is one of the main types of hydro turbine. But it is always appeared vibration, noise and power fluctuation which caused by pressure fluctuations under partial load conditions[1]. The pressure fluctuations generally are induced by the cavitation vortex rope in the draft tube and the rotor-stator interactions at the vaneless region which between the guide vane outlet and runner inlet. The cavitation vortex rope may result in high amplitude pressure fluctuation which can affected the operation stability and caused fatigue damage[2]. It is important to distinguish the inducement of the pressure fluctuations. Then it can be avoid in the design process of Francis turbine. But due to the flow in different components of hydro turbine are interaction with each other, it is important to analyze the signal of pressure fluctuation to identify the inducement of the instability of hydro turbine. Although commercial CFD tools have been widely used to investigate the internal flow[3-5], it's accuracy still need to be validated by experiment. Sakamoto et al.[6] is measured the flow velocity component in a horizontal cross-section of the draft tube cone by Laser Doppler Velocity (LDV). Favrel et al.[7] concentrated on linking the intensity of the excitation source to the
vortex rope in the draft tube. Although large quantity of research dealing with the part-load issue\cite{8,9}, the accurate physical mechanism that drives the excitation source is not clear. Meanwhile, the relationship among the pressure fluctuation at different component of hydro turbine has not been established, especially for the high head Francis turbine. In order to better understand the correlation among the pressure fluctuation at different component of high head Francis turbine, the pressure fluctuation measurement of a reduced scale high head Francis turbine model was carried out under partial load in this paper. By analyzing the pressure fluctuation signal of all measuring points, some information and rules are got.

2. Experiment set-up

The test case is a 1:7.3 reduced scale physical model of a high head Francis turbine which the maximum head is 338.96m and the rated head is 301.0m. The high head Francis turbine model was installed on the test rig FTB1 at the FINE institute of hydraulic machinery. The test system was given in Figure 1.

The test head $H_M$ for the Francis turbine model is 30m. The nominal runner diameter of the tested turbine model is $D_1$=0.5m. The number of stay vanes is 23, and the number of guide vanes is 24. The runner blades are composed of 15 long blades and 15 splitter blades. The unit speed $n_{11}$ of the best efficiency point(BEP) is 62.5rpm and the unit discharge $Q_{11}$ of the BEP is 228 l/s. The relative height of guide vane is 0.12.

In this paper, the pressure fluctuation signals at different parts of the turbine under two working conditions were measured and analyzed. The measuring points in the draft tube cone were placed on the section which is 0.3 times runner outlet diameter($D_2$) away from the draft tube inlet. The measuring points in the elbow were placed on the section which at 45° to horizontal direction. The measuring points at the vaneless region were placed between the guide vane outlet and the runner inlet. The distribution of all the measuring points is shown in Figure 2.

In this paper, the stability of the hydro turbine in the operation can be reflected accurately. In this paper, the pressure fluctuation data and stability analysis are carried out for two conditions shown in the Table 1. Among them, the power of condition A is 35% rated power and the power of condition B is 50% rated power. Both of them are belong to deep part load conditions.
Table 1 Parameters of each test condition

| Condition | Opening | Unit speed (rpm) | Unit discharge (m³/s) | Test head (m) | Actual rotating frequency (Hz) |
|-----------|---------|------------------|-----------------------|--------------|--------------------------------|
| A         | 6°      | 67.6             | 0.0774                | 30           | 12.35                          |
| B         | 10°     | 67.6             | 0.134                 | 30           | 12.35                          |

3. Results and analysis

3.1. Definition of pressure fluctuation amplitude

A dimensionless characteristic amplitude is used to represent the magnitude of pressure fluctuations. The calculation formula of this dimensionless characteristic amplitude is given as follows:

\[ Amp = \frac{p_i - \bar{p}}{\rho g} \]  (1)

where \( p_i \) is the measured instantaneous pressure, \( \bar{p} \) is the mean value of the pressure collected in sampling interval, \( \rho \) is the density of water, \( g \) is the acceleration of gravity.

3.2. Stability analysis of pressure fluctuation under condition A

The pressure fluctuation data at all measuring points are obtained by pressure fluctuation sensor. The time-domain signals are shown in Figure 3.

![Figure 3](image-url)

It can be seen from Figure 3 that the amplitudes of the time-domain signals obtained from the two measuring points at the top cover are different. It means that the flow in front of the turbine runner inlet has obvious axial asymmetry. The time-domain signals were obtained from the two measuring points at the draft tube cone with the same characteristics. Frequency domain analysis of all the pressure fluctuations were done by FFT transform. The method of FFT transform is usually expressed the magnitude of the spectrum components in engineering units. The frequency spectra of all the measuring points are presented by a waterfall diagram as Figure 4 shown.
Although the method of FFT transform gives the amplitude of each frequency component, the levels of pressure fluctuation are determined by the peak to peak values of $Amp$. The peak to peak values are defined with the 97% confidence value. After the pressure pulsation levels are presented, they are normalized by the following equation (2).

$$H = \frac{\Delta Amp}{H_M} \times 100\%$$ (2)

where $\Delta Amp$ is the peak to peak values of $Amp$ with the 97% confidence value, $H_M$ is the net operating head of model turbine, $H$ is the pulsation levels.

| Dominant frequency (Hz) | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 | Point 6 |
|-------------------------|---------|---------|---------|---------|---------|---------|
| Pulsation levels $H$ (%)| 2.96    | 2.08    | 5.17    | 3.93    | 2.204   | 3.08    |

Due to the runner rotational frequency is 12.35 Hz at condition A, it can be seen from table 2 that the dominant frequency of all the measuring points is about 0.36 times the runner rotational frequency. The maximum pressure pulsation level of all the measuring points is 5.17%, which is appeared on the measuring point 3 of the draft tube cone. The pressure pulsation level of another measuring point on the draft tube cone is 3.93%, which is indicated that the cavitation vortex rope in the draft tube has an irregular spiral shape under part load condition. This can be confirmed by the following camera image in Figure 5.

![Figure 4](image_url)

**Figure 4** Frequency spectra diagram of pressure fluctuation under condition A

3.3. Stability analysis of pressure fluctuation under condition B

The time-domain signals of pressure fluctuation under condition B are shown in Figure 6. According to compare the data of pressure fluctuation at corresponding measuring point between Fig. 4 and Fig. 6, a conclusion which the fluctuation amplitude is increased with the discharge and power decreases under deep part load conditions could be obtained. It means that the stability of the turbine deteriorate with the power decrease.
The method of FFT transform also be used to analyze the frequency spectra of the pressure fluctuation data under condition B. The obtained frequency spectra is given as Figure 7. The dominant frequency and the pulsation level are shown in Table 3.

According to the data is listed in Table 3, the dominant frequency of most measuring points is 0.32 times the runner rotational frequency, which is close to condition A. And a special phenomenon that the two measuring points on the draft tube cone has different dominant frequency was found. In the spectrum data of measuring point 4, the dominant frequency is 2Hz and the second order dominant frequency is 3.9Hz, which indicates that the pressure fluctuation component has not disappeared. Meanwhile, the 2Hz is the second order dominant frequency in the spectrum data of measuring point 3. This phenomenon is confirmed that the cavitation vortex rope in the draft tube has the characteristic of circumferential asymmetry, and it has two frequency components which are 3.9Hz and 2Hz. As can be seen in Table 3, the higher frequency of 3.9Hz caused by vortex rope is transmitted to the whole flow passage of the hydro turbine. Additionally, it has been shown that the energy dissipation of the high frequency pressure fluctuation component is less than the low frequency component.

Table 3 Dominant frequency and pulsation levels under condition B

|        | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 | Point 6 |
|--------|---------|---------|---------|---------|---------|---------|
| Dominant frequency (Hz) | 3.9     | 3.9     | 3.9     | 2.0     | 3.9     | 3.9     |
| Pulsation levels $\overline{H}$ (%) | 2.61    | 2.748   | 3.08    | 2.53    | 3.125   | 3.02    |
4. Conclusions
(1) According to the experimental data of pressure fluctuation under two deep part load conditions, the dominant frequency of the pressure fluctuation in the draft tube is about 0.3 times the runner rotational frequency.
(2) The cavitation vortex rope in the draft tube has the characteristic of circumferential asymmetry. Besides, it has proved that the pressure fluctuation caused by the cavitation vortex rope in the draft tube cone would be transmitted to the upstream and downstream components of hydro turbine.
(3) The maximum pulsation level $H$ is appeared on the draft tube cone, which is 5.17% in these two conditions. And the maximum pulsation level under condition B is 39.6% lower than that condition A. Therefore, the pressure fluctuation under relative high load condition is more stable than the relative low load condition.

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