Experimental Research on Pressure Pulsation and Stability of Giant Francis Turbine

Qinghua Geng*1

1 Datang Hydropower Research Institute Co., Ltd., Chengdu, Sichuan, 610045, China

*Corresponding author’s e-mail: dtddyxny@cdt-kxjs.com

Abstract. Pressure pulsation is an important factor affecting the stability of the turbine. The test studied the characteristics and laws of pressure fluctuations of giant hydraulic turbines to provide guidance for the design and stable operation of giant hydraulic turbines. The test used time-domain analysis and frequency-domain analysis methods to test and analyze the pressure pulsating real machine of giant hydraulic turbine. The test results show that the amplitude of pressure pulsation has a negative correlation with active power. The active power ranges from no-load to 40%P, and the pressure pulsation is mainly expressed as a high-frequency waveform with a frequency conversion of 8.8 to 24.4 times. The active power ranges from 40%P to 75%P, and the pressure pulsation mainly manifests as a low-frequency waveform with a frequency conversion of 0.19 to 0.28 times. Active power range from 75%P to 100%P, the amplitude of pressure pulsation decreases significantly. The above three load areas coincide with the vibration area of the unit, indicating that the hydraulic factor is the main factor affecting the stability of the unit.

1. Introduction

At present, high-parameters and large-capacity are the development direction of water turbines. The largest water turbine in the world is the water turbine of the Baihetan Hydropower Station under construction in China, with a single unit capacity of 1,000MW. The three important factors that usually affect the stability of a hydraulic turbine are hydraulic vibration, structural design and installation quality. The stability of a hydraulic turbine in operation is mainly affected by hydraulic factors, and pressure pulsation is the main cause of hydraulic vibration. So far, most studies have mainly carried out research on draft tube pressure pulsation through theoretical analysis, numerical simulation, model testing and other methods. Guo Na[1] used the method of model test to test the pressure pulsation of the turbine, and analyzed the characteristics of the pressure pulsation, which provided a reference for the stability research and structural design of the prototype turbine; Tang Ning[2] conducted a comprehensive analysis of the formation mechanism and influencing factors of the tail water vortex zone through a numerical analysis based on the slip grid, which provided a reference for predicting the tail water vortex zone through the operating conditions of the turbine in the design stage. Gui Zhonghua[3] studied the evaluation method of pressure pulsation through a water rise test of a unit. Zhang Fei[4] analyzed the change trend of the main frequency of draft tube pressure pulsation under partial load of the Francis turbine based on the water level test data of the Three Gorges Power Plant, and pointed out the limitations of the existing vortex frequency calculation formula. However, regardless of the refurbishment, there have not been any reports of quantitative calculation analysis research on real machines. This article attempts to measure the pressure pulsation, load and unit vibration data of a giant
hydraulic turbine on-site under real machine conditions, and uses time domain analysis and frequency domain analysis to analyze the pressure pulsation, active power and unit under constant water head.

2. Pressure pulsation analysis method

2.1. Time domain analysis
Time domain analysis \cite{5} is a basic analysis method for diagnosing and detecting pulsatile signals. The time domain waveform is a signal after noise processing and contains more information. The analysis of the time-domain waveform is mainly the analysis of the amplitude, mean and root mean square value. Through the analysis of whether these characteristic data exceed the set threshold and the change trend of the characteristic data over time, the health status of the analysis object is judged.

2.1.1. Amplitude analysis
The peak-to-peak value of the pressure pulsation in the time domain is calculated using the peak-to-peak value of the sampled data at a confidence level of 97\% as the amplitude of the test result.

2.1.2. Analysis of Means
The average value is used to evaluate whether the signal is temperature, and represents the central fluctuation of the pulsating signal change. The expression is:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i, t = 1,2,...,n$$

(1)

2.2 Time domain analysis
Frequency domain analysis is to form the frequency spectrum of the pulsating signal after the time domain waveform undergoes a fast Fourier transform (FFT), and analyze the frequency of the waveform. In the frequency domain, analysis is mainly performed from three basic frequency spectrums: amplitude spectrum, power spectrum, and cepstrum.

2.2.1 Amplitude spectrum analysis
The amplitude spectrum is a Fourier transform of the processed vibration signal from the original signal sampled by the sensor, and the frequency spectrum of the time domain vibration signal is calculated. The expression of the Fourier transform is:

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft} dt$$

(2)

2.2.2 Power spectrum analysis
The power spectrum is the stepwise representation of the signal power in the frequency domain, reflecting the size of the signal capability. The expression of the power spectrum is:

$$s(f) = \frac{x^2(f)}{T}$$

(3)

2.2.3 Cepstrum analysis
Cepstrum can effectively detect the periodic components in the complex spectrum, and its expression is:

$$C_x(\tau) = F^{-1}[\log s(f)]$$

(4)
3. Experimental Research

3.1. Project Overview

A hydropower station is located on the main stream of the Dadu River in Sichuan. It has installed 4 giant Francis turbine generator sets with a single unit capacity of 650MW. The basic parameters of the turbine are shown in Table 1.

Table 1: Formatting sections, subsections and subsubsections

| Name                              | Parameter | Unit |
|-----------------------------------|-----------|------|
| Nominal diameter of runner (inlet diameter) | 670       | cm   |
| Maximum head                      | 217.70    | m    |
| Rated head                        | 200.00    | m    |
| Minimum head                      | 166.00    | m    |
| Rated output                      | 663       | MW   |
| Limited Data                      | 358       | m³/s |
| Installation elevation            | 1463.45   | m    |
| Suction elevation                 | -10.43    | m    |
| Maximum output                    | 870       | MW   |
| Rated speed                       | 142.9     | r/min|
| Fixed guide vane                  | 23        | piece|
| Movable guide vane                | 24        | piece|
| Runner blade                      | 16        | piece|
| Runaway speed                     | 255       | r/min|

3.2. Measuring point layout

In order to facilitate the analysis of the characteristic relationship between pressure pulsation and load of the giant Francis turbine, the measuring points of pressure pulsation and unit vibration are determined according to the influence of pressure pulsation on the stability[6], which are mainly arranged in draft tube pressure pulsation, no blade Zone pressure pulsation, swing of each bearing and other areas. The specific locations of monitoring points are shown in Figure 1.

Swing monitoring points: upper guide X direction, lower guide X direction, Turbine guide X direction, Turbine guide Y direction.
Vibration monitoring points: horizontal vibration of the top cover X, vertical vibration of the top cover Z.

Pressure fluctuation monitoring measuring points: draft tube measuring points D₁ and D₂, measuring point B under the top cover, and measuring point C in the leafless zone.

And other measuring points: active power, upstream and downstream water level, etc.

3.3. Test results

A continuous variable load test was carried out on a giant hydroelectric generating unit. The upstream water level was 1,600.51m, the downstream water level was 1476.48m, and the gross water head was about 184.03m. Under the current water head, the maximum loadable unit is 560.4MW, and the opening degree is 92.1%. The vibration, swing and pressure pulsation data of each part of the variable load test are shown in Table 2.

| Active power (MW) | Swing (μm) | Vibration (μm) | Pressure pulsation (kPa) |
|------------------|------------|---------------|--------------------------|
|                  | Upper guide bearing X direction | Lower guide bearing X direction | Turbine guide bearing X direction | Top cover X | Top cover Z | Draft tube A | Draft tube C | Top cover A | Leafless zone |
| 15.7             | 105.5      | 70.5          | 77.4                     | 66.5       | 8.7        | 221.3      | 126.3       | 94.7       | 7.4         | 32.4         |
| 39.6             | 106.5      | 69.0          | 71.3                     | 64.3       | 7.8        | 84.2       | 121.0       | 94.5       | 8.8         | 26.0         |
| 59.2             | 101.2      | 74.9          | 70.0                     | 66.9       | 7.9        | 62.8       | 116.1       | 90.1       | 7.8         | 25.9         |
| 80.1             | 105.7      | 73.7          | 71.1                     | 71.2       | 8.0        | 285.1      | 107.4       | 94.1       | 6.7         | 27.5         |
| 96.5             | 102.3      | 78.7          | 71.4                     | 72.5       | 8.6        | 102.7      | 99.7        | 80.1       | 7.8         | 28.1         |
| 115.6            | 103.4      | 78.0          | 69.7                     | 70.0       | 8.4        | 134.2      | 102.6       | 74.6       | 7.2         | 24.8         |
| 136.8            | 103.2      | 76.5          | 63.4                     | 62.6       | 7.4        | 45.4       | 102.4       | 72.5       | 12.1        | 22.2         |
| 156.9            | 102.6      | 77.3          | 56.5                     | 55.2       | 7.0        | 4.6        | 96.5        | 74.3       | 12.0        | 21.5         |
| 179.7            | 103.2      | 75.3          | 51.2                     | 52.7       | 6.3        | 2.4        | 76.0        | 63.0       | 10.0        | 20.8         |
| 201.2            | 102.5      | 79.2          | 44.0                     | 47.2       | 5.7        | 1.9        | 61.5        | 62.3       | 8.0         | 21.4         |
| 218.2            | 103.0      | 77.1          | 40.7                     | 44.7       | 4.8        | 1.3        | 48.5        | 44.9       | 6.4         | 25.4         |
| 245.6            | 106.5      | 92.3          | 64.4                     | 69.9       | 5.2        | 4.0        | 53.3        | 66.0       | 7.9         | 26.8         |
| 257.8            | 106.6      | 94.1          | 84.8                     | 92.1       | 6.0        | 1.9        | 44.7        | 64.6       | 8.4         | 29.0         |
| 279.8            | 108.4      | 98.9          | 92.4                     | 100.4      | 5.9        | 2.3        | 43.2        | 58.9       | 8.7         | 29.9         |
| 299.7            | 106.0      | 94.1          | 93.8                     | 102.1      | 4.8        | 1.6        | 34.7        | 44.2       | 8.5         | 29.5         |
| 320.5            | 105.4      | 94.6          | 78.8                     | 87.1       | 4.8        | 1.4        | 30.9        | 44.7       | 8.4         | 33.4         |
| 341.3            | 104.5      | 90.6          | 65.5                     | 72.0       | 4.7        | 1.9        | 29.1        | 41.6       | 7.5         | 25.6         |
| 360.4            | 102.7      | 90.3          | 54.5                     | 60.8       | 4.6        | 2.2        | 27.4        | 41         | 7.5         | 29.3         |
| 379.2            | 100.7      | 88.6          | 49.1                     | 54.8       | 5.2        | 3.8        | 32.0        | 31.6       | 6.8         | 29.7         |
| 398.2            | 99.7       | 85.7          | 42.1                     | 47.1       | 4.4        | 2.6        | 35.5        | 19.3       | 6.7         | 31.4         |
| 420.0            | 99.0       | 84.3          | 38.0                     | 43.0       | 4.6        | 1.6        | 22.4        | 19.6       | 10.3        | 22.1         |
| 439.5            | 99.0       | 85.1          | 38.1                     | 42.9       | 4.2        | 1.8        | 18.4        | 16.4       | 5.2         | 19.9         |
| 461.0            | 98.1       | 85.1          | 38.4                     | 43.5       | 4.3        | 1.6        | 18.0        | 17.9       | 3.5         | 17.6         |
| 481.5            | 98.1       | 85.1          | 39.2                     | 44.3       | 4.6        | 1.5        | 18.4        | 19.1       | 4.0         | 20.0         |
| 503.2            | 96.9       | 86.7          | 40.2                     | 45         | 4.8        | 1.8        | 38.7        | 17.7       | 16.5        | 27.5         |
| 522.5            | 97.6       | 86.4          | 41.4                     | 46.5       | 4.8        | 2.3        | 24.5        | 21.5       | 10.6        | 41.1         |
| 542.1            | 97.2       | 86.9          | 44.6                     | 48.4       | 5.8        | 2.8        | 24.0        | 24.4       | 5.6         | 59.0         |
| 560.4            | 96.7       | 87.5          | 55.2                     | 56.8       | 6.4        | 3.3        | 28.5        | 36.6       | 5.8         | 37.1         |
3.3.1. Analysis of tail water pressure fluctuation

- When the unit is connected to the grid with base load, the measured tail water pressure pulsation amplitude reaches the maximum value of 126.3 kPa; with the increase of load, the tail water pressure pulsation amplitude shows an overall decreasing trend, and the pressure pulsation amplitude has a negative correlation with the load. The relationship trend diagram between tail water pressure pulsation and load is shown in Figure 2.

- From the spectrum analysis of the tail water pressure pulsation of the entire load section, the grid-connected unit with base load to the unit with 40%P load range (0-220 MW). Affected by the turbulence at a small opening, the tail water pressure pulsation is mainly manifested as 21-58 Hz high-frequency waveform is 8.8-24.4 times the rotation frequency. The spectrum analysis diagram of the tail water pressure pulsation when the No. 1 unit carries a load of 115.6 MW is shown in Figure 3.

- The unit has a load range of 40%~75%P (220 MW ~ 420 MW). Affected by the draft tube vortex, the tail water pressure pulsation is mainly manifested as a low frequency waveform of 0.49~0.66 Hz, which is 0.19~0.21 times the rotation frequency. The pressure pulsation amplitude is significantly reduced compared to the low load area. The spectrum analysis diagram of the tail water pressure pulsation when the unit is loaded with 299.7 MW is shown in Figure 4.

- The unit has a load range of 75%~100%P (420 MW ~ 560 MW), the amplitude of tail water pressure pulsation is obviously reduced, and the unit runs stably.

![Figure 2](image1.png)  
**Figure 2** Relationship between pressure pulsation and load

![Figure 3](image2.png)  
**Figure 3** Spectrogram of tail water pressure fluctuation spectrum with a load of 115.6 MW
3.3.2. Swing analysis

- In the entire load range, the upper guide swing amplitude of the unit is small and has no obvious change; the lower guide swing is affected by the pressure pulsation of the draft tube, and its amplitude increases slightly in the 240MW~340MW load range, with a maximum value of 100.4 μm, much smaller than the limit value required by the regulations, and there is no obvious change in the rest of the load interval.

- The swing of water conductance varies slightly from the base load of the unit to the 220MW load range and 240MW~400MW load range of the unit and the load range of 240MW~400MW due to the small opening turbulence and draft tube vortex. The maximum value is 102.1μm, much smaller than the limit value required by the regulations, and there is no obvious change in the rest of the load interval. See Fig. 5 for the trend chart of swing amplitude of Unit 1; see Fig. 6 for the frequency spectrum analysis chart of water conductance swing of Unit 1 with a load of 299.7MW.

![Figure 4](image-url)  
Figure 4: Spectral diagram of tail water pressure fluctuations with a load of 299.7MW

![Figure 5](image-url)  
Figure 5: Relationship between swing amplitude and load
4. Conclusion

- Through the pressure pulsation and vibration test of a certain hydraulic turbine, the unit load is divided into three load intervals. The interval division is consistent with the low-efficiency operation area, hydraulic vibration area and stable operation area in the test report of the unit's full head vibration area test. The main factor that affects the stable operation of the unit under load is the hydraulic factor.
- The unit load range 0-40%P is a low-efficiency working condition area, and the pressure pulsation is mainly manifested as a high-frequency waveform of 8.8-24.4 times the frequency. In this working condition area, affected by the turbulence at a small opening, the tail water pressure pulsation and the vertical vibration amplitude of the roof are relatively large, and the unit operation stability is relatively poor.
- The unit load range from 40%P to 75%P is the low-frequency vortex hydraulic vibration zone; in this range, the amplitude of tail water, leafless zone, water guide swing and lower guide swing increases slightly, mainly 0.19~0.28 Low frequency waveform with double frequency.
- The load range of the unit above 75%P is an efficient and stable operation area. In this interval, the water pressure pulsation, vibration and swing amplitude are significantly reduced, and the unit is operating stably.

References

[1] Guo Na, Lu Chi, Yao Dan, Yang Bo. Experimental study on pressure fluctuation of Francis turbine model[J]. Hongshuihe. 2018(12)
[2] Tang Ning. Numerical simulation study and experiment on vortex pulsation of Francis turbine[D]. Zhejiang University. 2018(06)
[3] Gui Zhonghua, Le Zhenchun, Dong Yangwei, Tang Yongjun, et al. Research on pressure fluctuation evaluation method of Francis turbine. Hydropower and Pumped Storage. 2018(8)
[4] Zhang Fei, Gao Zhongxin, Pan Luoping, Ge Xinfeng. Experimental study on pressure fluctuation of draft tube of Francis turbine under partial load[J]. Journal of Hydraulic Engineering. 2011(10)
[5] Sheng Meiping, Yang Honghui. Vibration signal processing [M]. Publishing House of Electronics Industry. July 2017
[6] GB/T 17189-2017 Hydraulic machinery (water turbine, storage pump and water pump turbine) vibration and pulsation field test procedure [S]. China Standard Press. 2018