Comparative Evaluation of Vibration Test Results for Various Pumped Storage Power Plants

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ABSTRACT

Hydraulic excitation, which is clearly connected to the cascade combination created by the number of runner blades and the number of moveable guide vanes of the unit, is the primary source of excitation force for the structural vibration of the plant of the pumped storage power station. The minimum pitch diameter number of the unit has a direct bearing on the excitation force's primary frequency. The structural vibration spectrum caused by the cascade combination unit with the minimum pitch diameter number equal to 1 or 2 typically manifests as a single main frequency and a large vibration amplitude of the plant, according to an analysis of vibration test data from typical pumped storage power station plants.The plant's vibration amplitude is quite low, and the structural vibration spectrum induced by the cascade combination unit with the minimum pitch diameter number equal to 4 is comparatively scattered. According to the aforementioned research, employing a cascade combination unit with a minimum pitch diameter number of 4 significantly reduces the plant's vibration amplitude, which is very advantageous for the plant's vibration reduction.

Keywords: Vibration, Pumped Storage, Power Plant, Hydraulic excitation, Power station.

1. Introduction

Pumped storage has the most advanced technology, the greatest economics, the largest development conditions, and is a clean, flexible, low-carbon power source [1]. It works well in tandem with thermal, nuclear, solar, and wind energy sources. In order to build a new type of power system with renewable energy as its main source, it is imperative that the development of pumped storage be accelerated. This will ensure that the power system operates safely and steadily and will also provide a significant guarantee for the large-scale development of renewable energy.The vaneless area space between the runner inlet and the active guiding vane is severely constrained because of the diversion channel's length, the pressure side's high pressure, and the unit's design, which is slanted toward runoff type. A high-frequency, strongly-amplitude dynamic and static interference pressure pulsation is formed by the vaneless region of the pump turbine.

Vibration, noise, and different instability issues can arise in different areas of the water guidance mechanism due to the propagation, interference, and superposition of the first and higher harmonics of the pulsation in the volute flow channel, the pressure steel pipe, and other channels.Three different types of vibration sources are available for the hydropower station's plant vibration: mechanical, electromagnetic, and hydraulic [2] sources. According to related research, hydraulic vibration source [3, 4], which is pressure pulsation in the unit's flow channel, is the primary cause of vibration for the pumped storage power station unit and plant. Common sources of hydraulic vibration include pressure pulsation in the draft tube and hydraulic excitation and resonance brought on by dynamic and static interference in the vaneless section of the pump turbine. There is comparatively high plant vibration in a few of the China-operated pumped storage power plants.Later on, by replacing the runner, for example, a certain amount of the plant vibration is mitigated [5-8]. According to the recorded data, the pump turbine's many frequencies and dynamic and static interference frequencies are essentially what cause the major vibration frequency of the heavily vibrating pumped storage power plant.

This study analyzes the unique impact of the pressure pulsation produced by the operation of typical varied cascade combination units on the vibration characteristics of the plant structure. It also calculates and counts the vibration characteristics of the measured plant structure.

2. Examining the Vibration Properties of the Pumped Storage Power Station Unit and Plant

The primary frequency of plant vibration response while the unit works at varying loads is multiple frequency of the unit's overcurrent frequency. The pulsing pressure in the unit's flow channel is the primary source of excitation for the plant vibration.

Cascade combinations are those in which the unit's number of active guide vanes and number of runner blades match. Early pumped storage power plant units often had a cascade combination of 9 + 20 or 7 + 20. novel pump turbine types with novel cascade combinations—such as (5 + 5)/16, 9/22, 13/22, 11/20, and so on—continue to emerge as a result of domestic units' increased capability for research and development. Of these, the 5 + 5)/16, 9/22 type has been the most common type for the medium and high head section.The primary frequency of the plant vibration is primarily two or three times the overcurrent frequency, which is strongly connected to the cascade combination type of the unit, according to a statistical analysis of the plant vibration data taken from the test of the functioning power station.

The primary frequency characteristics of the plant vibration of several pumped storage power plants are derived from the summary of the on-site vibration test analysis findings from various research institutes, as indicated in Table 1.

Table 1. Statistics on vibration frequency of some pumped storage power plants

No.	Power station	Single machine capacity (MW)	Speed (rpm)	Number of runner blades	Number of active guide vanes	Blade over current frequency (Hz)	Main frequency of plant vibration (Hz)
1	Shisanling	200	500	7	16	58.33	116.7
2	Baishan	150	200	7	20	23.33	70
3	Xilongchi	306	500	7	20	58.33	175
4	Tongbai	306	300	7	20	35	175
5	Liyang	250	300	7	20	35	105
6	Zhanghewan	250	333.3	9	20	50	100
7	Xianju	375	375	9	20	56.25	112.5
8	Dunhua	350	500	9	20	75	150
9	Fengning(I)	306	428.6	9	20	64.29	128.6
10	Shenzhen	306	128.6	9	20	64.29	128.6
11	Hongping	306	500	9	20	75	150
12	Xianyou	306	428.6	9	20	64.29	128
13	Pushihe	306	333.3	9	20	50	100
14	Taian	250	300	9	22	45	180
15	Guangzhou(I)	306	500	9	20	75	100
16	Bailianhe	306	250	9	20	37.5	75
17	Heimifeng	306	300	9	20	45	90
18	Jinzhai	300	333.3	13	22	72.2	144.4

The Pushihe pumped storage power station, Liyang pumped storage power station (Unit 1#~3#), and Xianyou pumped storage power station are the power stations of the unit that have a cascade combination of nine runner blades and twenty guide vanes. This kind of cascade combo is widely available right now. The primary frequency of the plant vibration is primarily represented as twice the runner blade's overcurrent frequency when the unit is operating at full load.

The Shisanling pumped storage power station is the principal example of a power station with a cascade combination of seven runner blades and sixteen guide blades. The primary frequency of the plant vibration while this kind of cascade combination is operating at full load is mostly represented as two times the runner blade's overcurrent frequency.

Among the power plants having a cascade arrangement of 20 guide blades and 7 runner blades per unit are the Baishan Pumped Storage Power Plant. The primary frequency of the plant vibration is mostly represented as three times the overcurrent frequency of the runner blade when the unit of this kind of cascade combination runs at full load.

The Guangzhou(I) pumped storage power station and the Taian pumped storage power station are two of the power stations in the unit with a cascade combination of 26 guide blades and 9 runner blades. Three times the runner blade's overcurrent frequency is the primary reflection of the plant vibration when this kind of cascade combination unit is operating at maximum load.

3. The Law of Hydraulic Excitation in Various Cascade Combination Units

Hydraulic stimulation is the primary source of vibration in pumped storage power station units and facilities. The quantity of runner blades and guide vanes has a direct impact on the hydraulic excitation properties of units with various cascade configurations [9].

The moveable guiding vane of the pump turbine's output edge is comparatively thick, which is the primary cause of the hydraulic excitation generated by the unit operation. The unit creates an irregular flow field at the guide vane's exit as the water flow passes through the moveable vane due to the wake effect. The water flow entering the spinning runner under the influence of water pressure also regularly disrupts the potential flow at the runner's entrance. Both dynamic and static interference will be produced by the vaneless space between the runner and the moveable guide vane, and the pressure pulse in the volute will exhibit a periodic law overall [10]. The plant vibrates and makes noise due to the pressure pulsation in the volute; also, there is a comparable periodic relationship between structural noise and plant vibration.

Equation [11] provides a description of the pressure field created by the interaction between the guide vane and the runner blade:

$$f(x) = \frac{B}{2}\cos[mZ_r\omega_n t - (mZ_r - nZ_g)\theta_s + \varphi_n - \varphi_m] + \frac{B}{2}\cos[mZ_r\omega_n t - (mZ_r + nZ_g)\theta_s - \varphi_n - \varphi_m] \quad (1)$$

where B is the pressure pulsation's average amplitude. Two integers are m and n. The angular coordinate θs is strongly associated with the angular coordinates of the spinning system (runner) and the static system (volute, guide vane, and top cover). The quantity of active guiding vanes is denoted by Z_g. Z_r denotes the quantity of running blades. The unit's rotational speed is denoted by ω_n.

Pressure pulsation is a function of time t and spatial angle θs, as demonstrated by equation (1).

Its many low-order and high-order hydraulic excitation modes are dictated by the cascade combination made up of the quantity of guide vanes and runner blades.

The pitch diameter number *k* is described as

$$k = mZ_r \pm nZ_g$$

(2)

The minimum pitch diameter number *k*1 and the maximum pitch diameter number *k*2 are described as

$$k_1 = mZ_r - nZ_g \quad (3)$$

$$k_2 = mZ_r + nZ_g \quad (4)$$

$$k_{min} = \text{Min}(|k|) = \text{Min}(|k_1|) \quad (5)$$

There are several hydraulic excitation modes in the unit's flow channel, as shown by Eq. (1). The bigger the appropriate pitch diameter number |k| and the lower the vibration amplitude of the hydraulic excitation force, the higher the harmonic order of the hydraulic excitation mode. Conversely, a smaller pitch diameter number |k| and a bigger vibration amplitude of the hydraulic excitation force correlate to a lower harmonic order of the hydraulic excitation mode [12]. Thus, the primary vibration excitation force of pressure pulsation is the harmonic corresponding to the lowest pitch diameter number k_1, and the maximum predominant vibration excitation force of pressure pulsation is the hydraulic excitation force corresponding to k_{min}.

The hydraulic excitation mode created by the static and dynamic interference causes the flow components, such as the guide vane and volute, to vibrate while the pumped storage unit is operating. The unit speed and the cascade combination mode define the vibration amplitude and frequency of the hydraulic excitation force.

The overcurrent frequency of the active guide vane fr and its multiple frequency is the frequency of the hydraulic excitation force applied to the runner:

$$f_r = nZ_g f_n \quad (6)$$

The overcurrent frequency of the runner blade fs and its multiple frequency is the frequency of the hydraulic excitation force on the guide vane, head cover, and volute:

$$f_s = mZ_r f_n \tag{7}$$

where, f_n is the unit rotation frequency.

The amplitude and frequency characteristics of the hydraulic excitation force for the operational pumped storage power plant may be predicted and assessed using Equations after the unit speed and cascade combination are known. (1)–(7).

Hydraulic excitation is the primary source of vibration in the pumped storage power station facility. Through the head cover and volute, the pressure pulsation is transferred to the peripheral concrete support, where it is subsequently transferred to the plant structure, resulting in structural noise and vibration of the plant structure. Equations (1) through (7) can, to some extent, represent the plant vibration characteristics of a pumped storage power station.

4. Properties of Vibration in Measured Pumped Storage Power Systems

Through measured experiments, the authors have gathered a large amount of vibration data of the pumped storage power station plant construction with different cascade combinations. Hydropower stations like as Baishan, Heimifeng, Shisanling, Pushihe, and Jinzhai are among the typical hydropower stations that have been under test. As indicated in Table 2, the unit's minimum pitch diameter figures in the aforementioned typical pumped storage power facilities are also counted. These plant structures' vibration data are compared and examined simultaneously. It should be mentioned that the runner in the Heimifeng pumped storage power plant has been changed owing to the apparent vibration of the #4 unit.The original 9/20 cascade combination of the replacement 4# unit has been replaced with the current (6 + 6)/20 cascade combination[8].

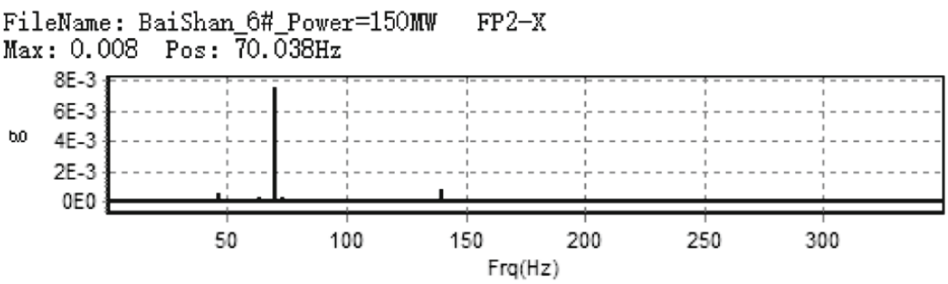
Table 2. Statistics for minimum pitch diameter of typical pumped storage power plant units

Power station & cascade combination	f_n (Hz)	n	m	k_1	f_s (Hz)	f_s/f_n
Pushihe	5.555	1	2	−2	100.0	18
9/20		2	4	−4	200.0	36
Shisanling	8.333	1	2	−2	116.7	14
7/16		2	5	3	291.7	35
Baishan	3.333	1	3	1	70.0	21
7/20		2	6	2	140.0	42
Heimifeng	5.000	1	2	4	120.0	24
(6 + 6)/20		2	3	−4	180.0	36
Jinzhai	5.555	1	2	4	144.4	26
13/22		2	3	−5	216.6	39

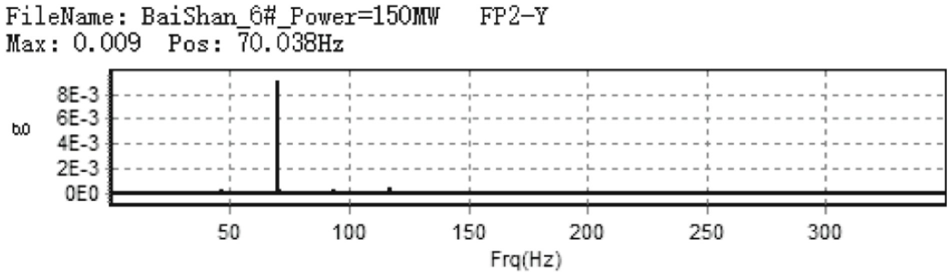
4.1 Examination of the Measured Pumped Storage Power Station Plant's Vibration Spectrum Features

The observed data of the plant vibration of typical pumped storage power plants were subjected to a frequency spectrum analysis. The main frequencies of the actual plant vibration are very consistent with the frequencies of the hydraulic excitation mode corresponding to k_1, as can be seen from the calculated frequencies of the hydraulic excitation mode corresponding to the minimum pitch diameter number (see Table 2). This indicates that the hydraulic excitation force of various cascade combination units is primarily the hydraulic excitation mode with n = 1 or n = 2 and $k = k_{min}$.

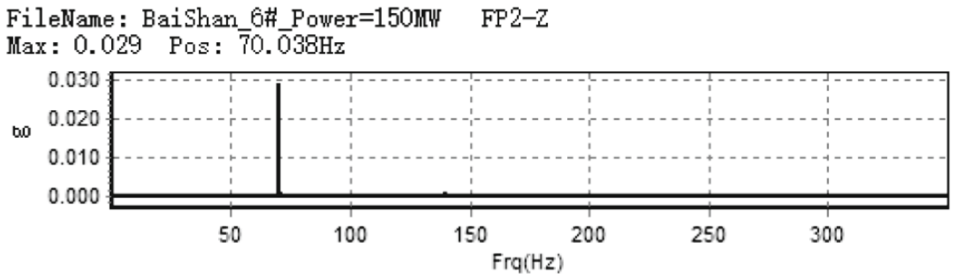
Regarding the power plants with a minimum pitch diameter of one unit (Baishan pumped storage power station) and a minimum pitch diameter of two units (Pushihe pumped storage power station and Shisanling pumped storage power station), in terms of the unit. The dominating frequency is clearly visible in the vibration spectrum of the plant structure of the three pumped storage power plants. It is equal to m times the runner blade's overcurrent frequency. Fig. 1 displays the vibration fourier spectrums of the Baishan power plant.



(a) X-direction vibration fourier spectrogram



(b) Y-direction vibration fourier spectrogram

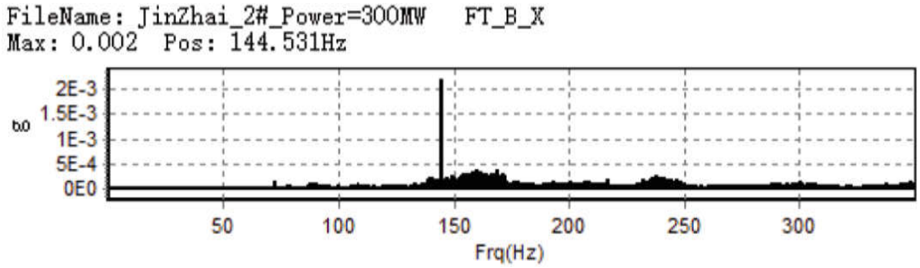


(c) Z-direction vibration fourier spectrogram

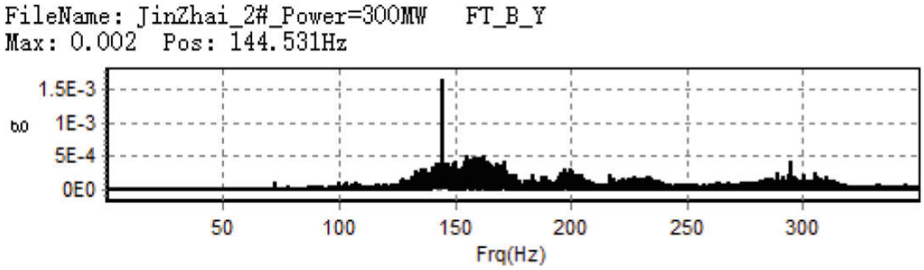
Fig. 1. Three orthogonal direction's vibration frequency spectrograms of a measuring point in Baishan power station

The main vibration frequency of the plant structure includes m times the frequency of the overcurrent frequency of the runner blade for power stations with the minimum pitch diameter kmin = 4 of the unit, such as Jinzhai pumped storage power station and Heimifeng pumped storage power station (4# unit). However, the vibration amplitude corresponding to the frequency is not significant. Fig. 2 displays the vibration fourier spectrograms of the Jinzhai power plant. Plant vibration energy is dispersed along a large frequency range. The two pumped storage power plants have far reduced plant structural vibration amplitudes than comparable power stations.

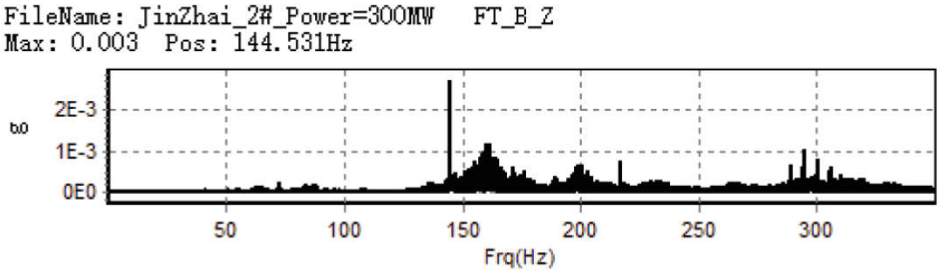
The 4# unit of the Heimifeng Power Station uses the 6 + 6)/20 cascade combination type. A runner type known as 6 + 6 has six long and six short blades. A single length runner blade cannot match the complexity and diversity of its hydraulic excitation mode. The primary frequency features of the hydraulic excitation mode of the cascade combination of 12/20 and 6/20 are contained in the primary frequency characteristics of the hydraulic excitation force. The spectrum has a lot of distinctive frequencies, although the vibration amplitude is not very large.



(d) X-direction vibration fourier spectrogram



(e) Y-direction vibration fourier spectrogram



(f) Z-direction vibration fourier spectrogram

Fig. 2. Three orthogonal direction's vibration frequency spectrograms of a measuring point in Jinzhai power station

5. Conclusions

There are notable differences in the excitation force amplitudes of the pressure pulsation of the static and dynamic interference of the units with varying cascade configurations. The results of the frequency spectrum analysis of the measured vibration data in the typical structures of pumped storage power plants also reflect the frequency characteristics of the dynamic and static interference, suggesting that hydraulic excitation force is the primary source of vibration in pumped storage power plants.

The vibration spectra of the plant structure has a substantial single dominant frequency that is m times the runner blade's overcurrent frequency when the unit's minimum pitch diameter number is 1 or 2.

Even if the plant structure's main vibration frequency includes m times the frequency of the runner blade when the unit's minimum pitch diameter number is 4, the main vibration frequency's amplitude is not very high. The vibration amplitude of the plant structure has significantly decreased, and the plant vibration energy is dispersed across a large frequency range.

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