Research on Vibration Characteristics of Powerhouse Structure of Variable Speed Unit Section in Fengning Pumped Storage Power Station

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Abstract: Taking the powerhouse of 12# variable speed unit section in Fengning pumped storage power station as a research object, a three-dimensional finite element model of the powerhouse structure was established. Firstly, the modal analysis method was used to calculate and research the natural vibration characteristics of whole and local structures of the powerhouse. Then, based on the field measured pressure pulsation data, the vibration responses of the powerhouse structure were simulated under the action of hydraulic vibration source. And referring to the relevant vibration control standard of powerhouse, the vibration responses of the powerhouse were analyzed and evaluated. The results show that the top 20 natural frequencies of the whole structure of the powerhouse range from 13.71 to 34.00 Hz, and the top 3 vibration modes are mainly the whole vibration of the structure above the volute layer. The calculation values of natural frequencies of the busbar floor and pillars are not significantly different from the measured values, indicating that the establishment of the calculation model and the setting of the boundary conditions are reasonable and effective. The maximum vibration responses of local structures of the powerhouse meet the vibration control standard of powerhouse under pumping and generating conditions.

1 INTRODUCTION

Pumped storage power station is a green, low-carbon, clean and flexible regulated power supply with the most mature technology, the best economy and the greatest potential for large-scale development (Zhou et al., 2023). With the development and needs of pumped storage power station construction, pump turbine unit is developing towards the direction of ultra-high head, large capacity, high speed and variable speed. As the supporting structure of unit, the powerhouse of hydropower station may experience whole or local vibration when subjected to exciting forces such as mechanical force, electromagnetic force and hydraulic force generated during the operation of unit (Gao et al., 2023). At present, vibration problems have been occurred on powerhouse structures of many pumped storage power stations in China when they are operating (Wang et al., 2023). Therefore, in-depth research on vibration characteristics of powerhouse is of great significance to effectively avoid the harmful vibration that may occur on the structure.

This paper took the powerhouse structure of 12# variable speed unit section in Fengning pumped storage power station as a research object. After completing the analysis of natural vibration characteristics of whole and local structures of the powerhouse, the vibration responses of the powerhouse structure under pressure pulsation were calculated, and the vibration safety of the powerhouse was analyzed and evaluated according to the vibration control standard of powerhouse. It is

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expected that the research results can provide a scientific basis for the design and safe operation of pumped storage power station.

2 CALCULATION MODEL AND PARAMETERS

2.1 Project Overview

Fengning pumped storage power station is located in the west of Chengde, Hebei Province, China. A total of 12 units with a capacity of 300 MW are installed in the main powerhouse, of which 11# and 12# units are variable speed units. Below the generator layer is an integral cast concrete structure, which is divided into six layers, including draft tube layer, volute layer, volute interlayer, turbine layer, busbar layer and generator layer from bottom to top. The power station adopts a structural type of one unit and one joint, and structural joints are set between the installation site and main powerhouse, and between the auxiliary powerhouse and main powerhouse.

2.2 Finite Element Model

The powerhouse structure of 12# variable speed unit section is taken as a research object. X direction is bounded by the left and right structural joints, Y direction is taken to the upstream and downstream side walls connected with the surrounding rock, and Z direction is taken from the bottom of concrete around the draft tube to the generator floor. Concrete structures such as floors, side walls, pillars, wind hood, turbine pier, concrete around volute and draft tube, as well as flow channel metal structures such as volute and draft tube are simulated in a finite element model. All concrete structures are segmented by three-dimensional solid elements, and all flow channel structures are simulated by shell elements. The finite element model of the powerhouse structure is divided into 231100 elements and 249727 nodes, as shown in Figure 1.

The powerhouse structure is simulated by elastic constitutive relationship, and the concrete grade is C30. The material parameters are shown in Table 1.

Table 1: Material parameters.

Material	Elastic modulus (GPa)	Poisson ratio	Density (kg/m^3)
C30	30	0.167	2500
Steel	200	0.300	7850

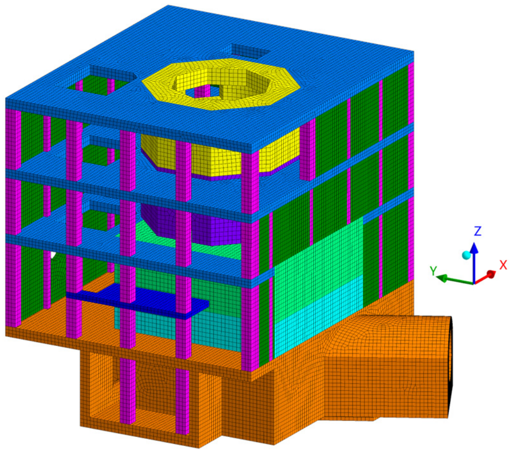


Figure 1: Three-dimensional finite element model of powerhouse structure.

2.3 Boundary Conditions

The left, right and top sides of the finite element model are set as free surfaces, and the other boundaries (the connection parts between the powerhouse and surrounding rock) are set as viscoelastic artificial boundaries.

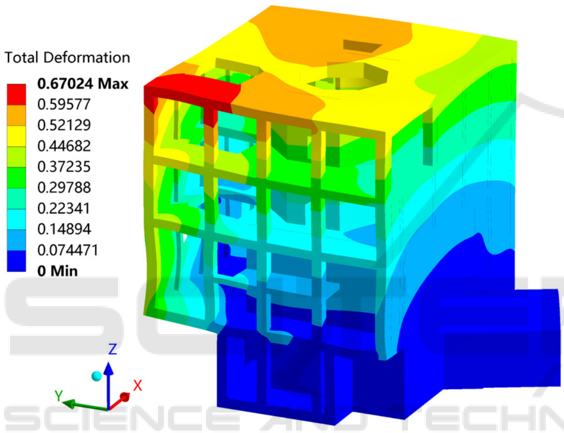
3 ANALYSIS OF NATURAL VIBRATION CHARACTERISTICS OF POWERHOUSE STRUCTURE

3.1 Natural Vibration Characteristics of Whole Structure

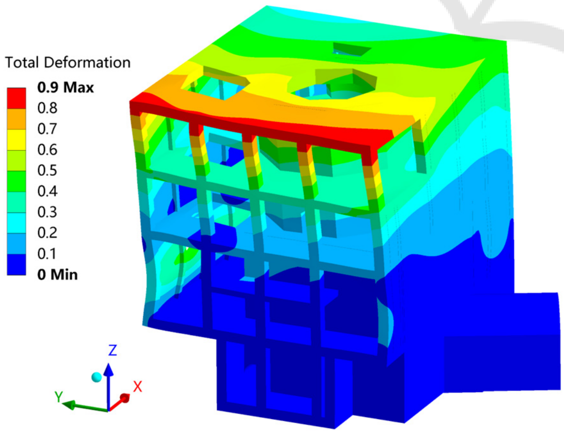
The calculation results of the top 20 natural frequencies of the whole structure of the powerhouse are shown in Table 2, and the top 3 vibration modes are shown in Figure 2. The top 20 natural frequencies of the whole structure of the powerhouse range from 13.71 to 34.00 Hz. The first vibration mode of the powerhouse is mainly X-direction vibration of the whole structure above the volute layer. The second vibration mode is mainly Y-direction vibration of the whole structure above the volute layer. The third vibration mode is mainly torsional vibration of the whole structure above the volute layer around Z axis. The other vibration modes are mainly the vertical vibration in local areas of the floors and the normal vibration in local areas of the side walls.

Table 2: Natural frequencies of whole structure

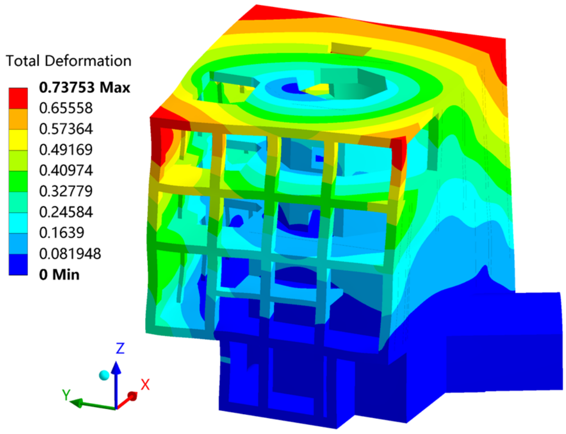
No.	Frequency (Hz)	No.	Frequency (Hz)	No.	Frequency (Hz)
1	13.71	8	27.40	15	31.38
2	15.06	9	27.84	16	32.14
3	18.73	10	28.34	17	32.54
4	21.79	11	29.06	18	32.93
5	22.46	12	29.61	19	33.42
6	25.30	13	30.16	20	34.00
7	26.30	14	30.78		



(a) First vibration mode



(b) Second vibration mode



(c) Third vibration mode

Figure 2: Top 3 vibration modes of whole structure.

3.2 Natural Vibration Characteristics of Local Structures

Due to the complex space structure of the powerhouse, the same vibration mode often shows simultaneous vibration of different parts. Therefore, it is very difficult to accurately calculate the natural frequencies of local structures we are concerned about by using the calculation method of natural frequencies of whole structure. Here, the massless foundation method is adopted, that is, the density of all the other structures except the local structure calculated is assigned as 0, and only their constraints on the local structure studied are considered.

Limited by the paper length, this paper mainly analyzes the natural vibration characteristics of the busbar floor and pillars. For the floor, because its horizontal vibration is relatively small, its vertical vibration should be the focus of attention. Similarly, for the pillars, their horizontal vibration should be emphatically analyzed. The number of peak points of the vertical first vibration mode of each area on the busbar floor and the number of pillars are shown in Figure 3, and the corresponding calculation results of natural frequencies are shown in Tables 3 and 4. As a comparison, the field test results of natural frequencies of the floor and pillars are also listed in Tables 3 and 4, in which the relative error expression between the calculation and test values of natural frequency is

$$Relative\ error = \frac{|Calculation - Test|}{Test} \times 100\% \quad (1)$$

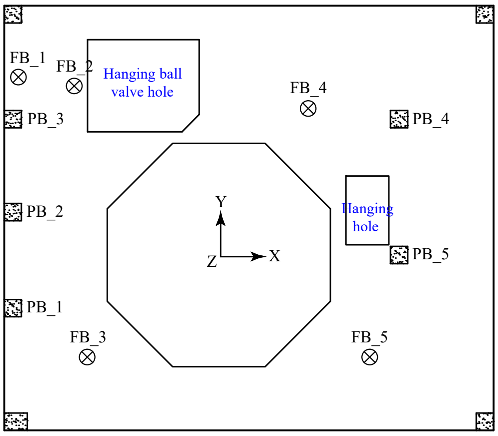


Figure 3: Numbers of peak points of vibration mode of busbar floor and pillars.

Table 3: Vertical first natural frequency of each area on busbar floor.

Peak point of vibration mode	FB_1	FB_2	FB_3	FB_4	FB_5
Test (Hz)	46.88	32.32	43.07	76.60	111.90
Calculation (Hz)	45.33	32.28	41.13	72.72	119.27
Relative error (%)	3.31	0.12	4.50	5.07	6.59

Table 4: Horizontal first natural frequency of each pillar on busbar layer.

Pillar		PB_1	PB_2	PB_3	PB_4	PB_5
X direction	Test (Hz)	—	—	77.98	79.98	71.48
	Calculation (Hz)	68.66	68.01	72.89	76.88	74.34
	Relative error (%)	—	—	6.53	3.88	4.00
Y direction	Test (Hz)	—	—	71.09	79.10	81.93
	Calculation (Hz)	68.27	69.30	69.66	76.20	76.71
	Relative error (%)	—	—	2.01	3.67	6.37

The maximum relative error between the calculation and test values of the vertical first natural frequencies of local areas of the busbar floor is 6.59%, and the maximum relative error between the calculation and test values of the horizontal first natural frequencies of the busbar pillars is 6.53%. In general, the difference between the calculation and test values of natural frequency of each structure is small, indicating that the calculation model established and the boundary conditions set in this paper are reasonable, and the calculation method is feasible.

4 ANALYSIS OF VIBRATION RESPONSES OF POWERHOUSE STRUCTURE

4.1 Vibration Control Standard of Powerhouse

As the support system of unit, the powerhouse is also a daily office space for the staff, so its structural design is very important to ensure the safety and comfort of the staff. At present, there is no unified evaluation standard for the vibration control of pumped storage power station powerhouse. In this paper, the vibration control standard of powerhouse is listed in Table 5 according to reference (Ma et al., 2013), which can be used as a quantitative basis for the prediction and control of powerhouse vibration.

Table 5: Vibration control standard of powerhouse.

Structure		Displacement (mm)	Velocity (mm/s)		Acceleration (m/s^2)	
			Horizontal	Vertical	Horizontal	Vertical
Floor	As building structure	0.2	5.0	5.0	1.0	1.0
	Human health evaluation	0.2	5.0	3.2	1.0	0.4
Wind hood, Turbine pier		0.2	5.0	5.0	1.0	1.0
Other building structures		0.2	10.0	10.0	1.0	1.0

4.2 Analysis and Evaluation of Vibration Responses of Powerhouse

Because the hydraulic vibration source occupies a dominant position, this paper mainly analyzes the vibration responses of the powerhouse structure under the action of hydraulic vibration source. In order to make the simulation results more accurate and reliable, the dynamic load comes from the measured pressure pulsation data in the flow channel,

Table 6: Maximum vibration responses of local structures under pumping condition.

Structure	Displacement (μm)			RMS velocity (mm/s)			RMS acceleration (m/s^2)		
	X	Y	Z	X	Y	Z	X	Y	Z
Generator floor	1.884	3.180	3.755	0.082	0.131	0.215	0.031	0.029	0.099
Busbar floor	1.413	2.664	3.838	0.077	0.107	0.215	0.035	0.039	0.086
Turbine floor	2.031	2.406	3.078	0.193	0.199	0.281	0.129	0.166	0.213
Wind hood	1.570	2.337	2.962	0.133	0.108	0.230	0.071	0.057	0.103
Turbine pier	1.874	2.184	2.479	0.163	0.146	0.417	0.124	0.097	0.363
Busbar pillar	1.755	3.177	1.896	0.139	0.125	0.120	0.060	0.049	0.038
Turbine pillar	1.984	2.945	1.695	0.272	0.168	0.118	0.132	0.074	0.066

Table 7: Maximum vibration responses of local structures under generating condition.

Structure	Displacement (μm)			RMS velocity (mm/s)			RMS acceleration (m/s^2)		
	X	Y	Z	X	Y	Z	X	Y	Z
Generator floor	1.722	2.379	4.148	0.105	0.125	0.308	0.035	0.037	0.153
Busbar floor	1.075	2.031	3.977	0.113	0.140	0.229	0.057	0.056	0.098
Turbine floor	1.839	2.425	3.327	0.206	0.225	0.417	0.134	0.183	0.261
Wind hood	1.379	1.749	2.367	0.131	0.118	0.259	0.069	0.058	0.111
Turbine pier	1.629	1.719	1.987	0.182	0.148	0.445	0.133	0.101	0.388
Busbar pillar	2.181	2.051	1.735	0.178	0.148	0.159	0.077	0.058	0.052
Turbine pillar	2.126	2.673	1.991	0.312	0.221	0.138	0.147	0.102	0.069

and the calculation method adopts the time history method. The time history calculation is divided into two working conditions: pumping and generating (full load). The selected representative load duration is 2 s, and the structural damping ratio is 0.02. The maximum vibration responses of typical local structures of the powerhouse under pumping and generating conditions are shown in Tables 6 and 7, respectively.

Compared with Table 5, the maximum displacement, root mean square (RMS) velocity and root mean square (RMS) acceleration of local structures of the powerhouse such as floors, wind hood, turbine pier and pillars are small under the two working conditions, which meet the vibration control standard of powerhouse, indicating that the risk of vibration damage of the powerhouse structure is very low under steady-state operating conditions.

5 CONCLUSIONS

The following conclusions are obtained:

(1) The top 20 natural frequencies of the whole structure of the powerhouse range from 13.71 to 34.00 Hz. The top 3 vibration modes are mainly the whole vibration of the structure above the volute layer, and the other vibration modes are mainly the vertical vibration in local areas of the floors and the normal vibration in local areas of the side walls.

(2) By comparing the calculation and test values of the vertical first natural frequencies of local

areas of the busbar floor and the horizontal first natural frequencies of the busbar pillars, it can be seen that there is little difference between the two values, indicating that the calculation model established and the boundary conditions set in this paper are reasonable end effective.

(3) The maximum vibration responses of local structures of the powerhouse such as floors, wind hood, turbine pier and pillars are small under pumping and generating conditions, which meet the vibration control standard of powerhouse, indicating that the risk of vibration damage of the powerhouse structure is very low under steady-state operating conditions.

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