Flow-excited vibration of a large-scale Axial-flow pump station with steel flow passageway based on FSI

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Abstract:

Instead of the traditional concrete passageway, a new type structure of pump station with steel passageway is proposed for rapid construction and elimination temperature cracks. However, flow-excited vibration in the operation process of the pump station is still a crucial issue in design. A numerical model considering the interactions of the 3-dimensional (3D) unsteady turbulent flow with the concrete structure and steel passageway was established. Vibration characteristics and transient vibration for a pump station were analyzed based on fluid-structure interaction (FSI) method to predict the vibration responses of the concrete structure and steel passageway, and assess the vibration safety of the pump station structure system.

Keywords: Axial-flow pump houses; Steel flow passageways; 3D unsteady turbulent flow; Fluid structure interaction; Flow-excited vibration

Introduction

Vibration is a common problem in the operation process of the pump station. This long-term vibration has influence on the durability of equipment and the health of staff. Serious vibration could affect the safety and reliability of the pump station [1]. As a result, for the large pump stations with steel passageways, a new type structure of pump station, it is very crucial to predict and assess the vibration response and safety of the pump station structure including steel passageways.

Although a lot of researches on the flow-excited vibration analysis of the pump were carried, fluid-structure interaction was usually not taken into account, in particular, the steel passageway. In this study, in order to obtain the vibration responses occurred in the large axial-flow pump station, a numerical model considering the interactions of the 3D unsteady turbulent flow with the concrete structure and steel passageway was established based on ADINA. The impressible continuity equation, reynolds average Navier-Stokes equation and $k-\omega$ turbulent equations were used to simulate the 3D whole passageway unsteady turbulent flow of the axial-flow pump of steel passageway pump station [2]. The FSI boundary in the interface of fluid and structure is used for the energy transition between them [3]. The vibration characteristics and transient vibration for a pump station were analyzed based on fluid-structure interaction (FSI) method to predict the vibration responses of the concrete structure and steel passageway, and assess the vibration safety of the pump station structure system.

Description of the numerical model

A designing pump station in East China was investigated. The typical section of the pump station is shown in Fig. 1. The main parameters are given in Table 1. A FSI model of pump station structure-steel passageway-fluid was established. The structural features and design proposal of the pump station (including concrete water inlet and outlet, concrete pump house structure, concrete supports, steel passageway and stiffening ribs) were simulated. The whole finite element model is shown in Fig. 2, where the *x*-axis of the coordinate system was vertical to the main stream, the *y*-axis was along the main stream, and the *z*-axis was upward vertically. The original point was in the impeller center. The concrete structure was discretized into 3D-solid elements; the steel passageway was discretized into shell elements; the stiffening ribs in the steel passageway was discretized into beam elements; the water in passageway was discretized into 3D-fluid elements; the upper structure and pump equipment were considered as added masses. The whole FEM model was totally discretized into 234120 elements, including 43488 3D-solid elements, 2730 shell elements, 2430 beam elements and 185472 3D- fluid elements. The normal constraint boundary was applied in the bottom and the wall vertical to the main stream of the concrete structure. In vibration analysis, single unit was investigated to improve the computational efficiency, as shown in Fig. 3 and 4. The finite element meshes of the steel passageway, stiffening ribs and water in passageway are shown in Fig. 5-7, respectively. The material parameters of the concrete structure, steel passageway and stiffening ribs are shown in Table 2. The dynamic elastic modulus of concrete was increased by 30%, and the Rayleigh damping was adopted with the damping ratio of 5% in the transient analysis.

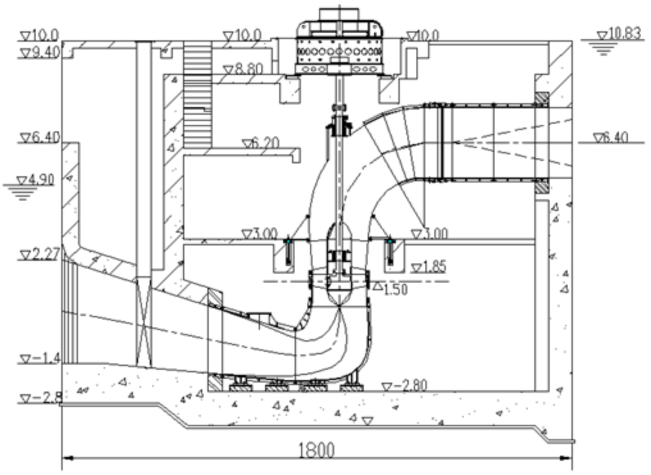


Figure 1. The typical section of the pump station

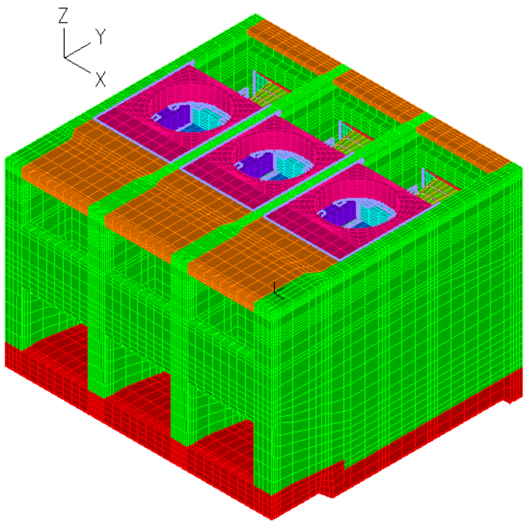


Figure 2. Whole finite element model

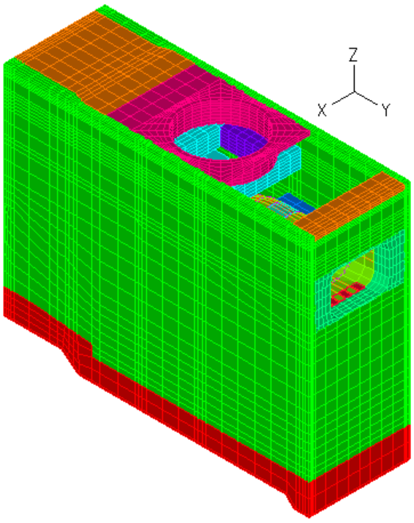


Figure 3. Finite element model of single unit

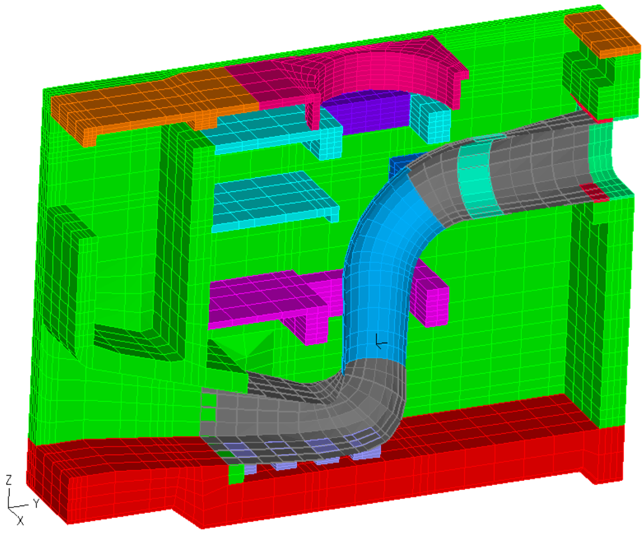


Figure 4. Cross-section of the mesh

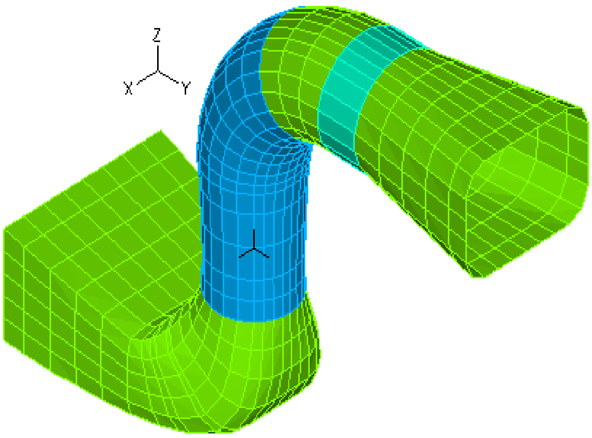


Figure 5. Finite element mesh of the steel passageway

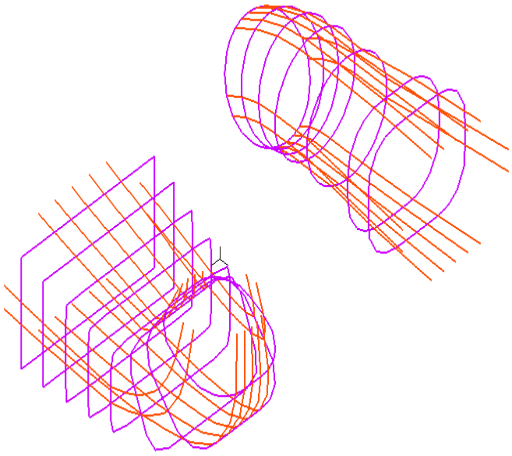


Figure 6. Finite element mesh of the stiffening ribs

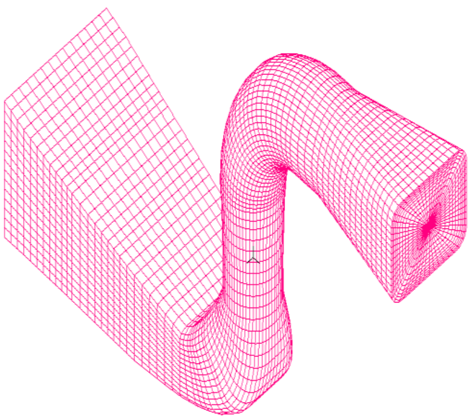


Figure 7. Mesh of the fluid

Table 1. Main parameters of the investigated pump station

Parameters	Q_d	H_d	n_d	Inlet width	Inlet height	Outlet width	Outlet height
Value	86 m^3/s	5.93 m	214.3 rpm	4.505 m	3.678 m	5.5 m	2.5 m

Table 2. Material parameters

	Density (kg/m^3)	Elastic modulus (GPa)	Poisson's ratio
Concrete structure	2400	28	0.167
Steel passageway	7800	210	0.3
Stiffening ribs	7800	210	0.3
Cast iron casing of pump	7800	210	0.3

Vibration characteristics analysis

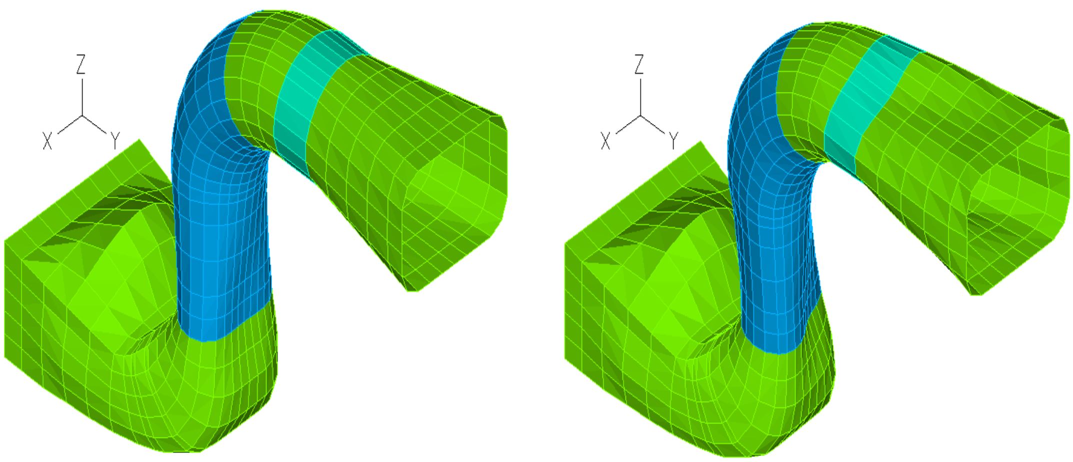
The vibration characteristics of the whole structure system in completion and operating conditions were analyzed. In operating condition, the fluid in the steel passageway was simulated by potential-based fluid elements. The first 15 order frequencies and the different main vibration positions are listed in Table 3.

Comparison of two conditions

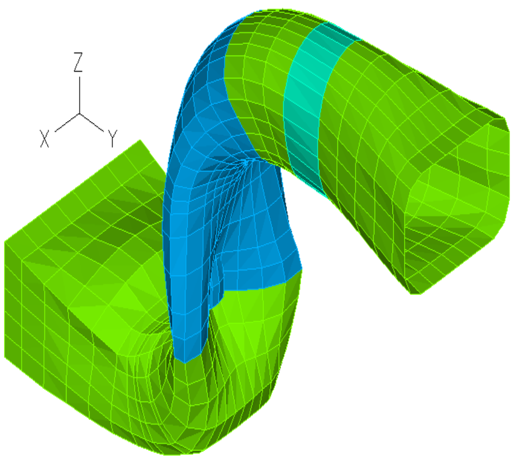
The results indicate that the water in the passageway has obvious effects on the vibration characteristics of the whole pump station system. All-order frequencies of the whole pump station system in operating condition are smaller than that in completion condition. Taking the fundamental frequency as an example, the fundamental frequency is 7.17 Hz in the operating condition, which is decreasing by 56.8 % compared with that in completion condition. The vibration modes of two conditions are different. For instance, the primary vibration position is the concrete structure in the first mode of vibration in completion condition, whereas the primary vibration position is the steel passageway in the first mode of vibration in operating condition. For the first mode of vibration, in operating condition the whole steel passageway vibrates along the *y*-axis, and inlet of the passageway vibrates along the z-axis upward vertically, whereas in completion condition the whole concrete structure vibrates along the y-axis. The first several modes of vibration are shown in Fig.8

Table 3. The first 15 frequencies in two conditions

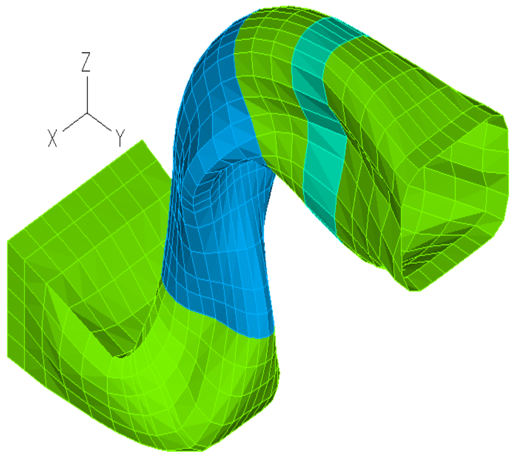
No.	Completion state		Operating state	
	Frequency (Hz)	Primary vibration position	Frequency (Hz)	Primary vibration position
1	16.60	Concrete structure	7.17	Steel passageway
2	32.72	Steel passageway	15.21	Concrete structure
3	36.97	Steel passageway	17.06	Steel passageway
4	38.30	Steel passageway	18.61	Steel passageway
5	42.93	Concrete structure	20.46	Steel passageway
6	44.97	Steel passageway	22.41	Steel passageway
7	46.25	Steel passageway	23.75	Steel passageway
8	49.82	Concrete structure	24.10	Concrete structure
9	50.92	Steel passageway	25.09	Steel passageway
10	56.25	Concrete structure	27.00	Steel passageway
11	56.80	Concrete structure	27.39	Steel passageway
12	57.49	Steel passageway	30.00	Steel passageway
13	58.10	Steel passageway	31.45	Concrete structure
14	59.98	Concrete structure	33.61	Steel passageway
15	62.59	Concrete structure	35.11	Concrete structure



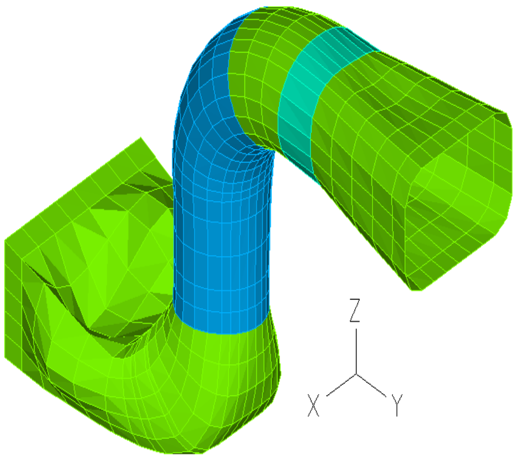
(a) The 1st mode of vibration **(b) The 3rd mode of vibration**



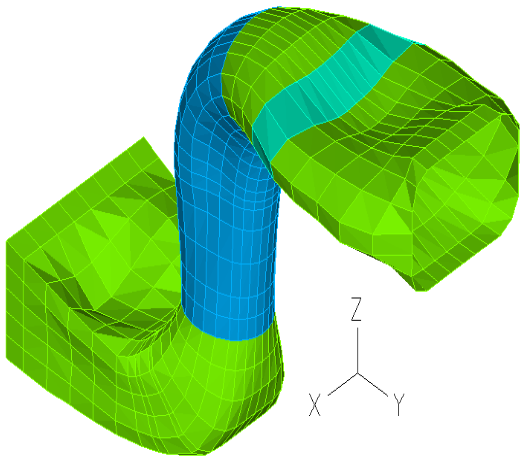
(c) The 4th mode of vibration



(d) The 5th mode of vibration



(e) The 6th mode of vibration



(f) The 7th mode of vibration

Figure 8. Vibration modes of the steel passageway

Resonance check

The resonance of equipment and structures must be avoided in operating condition. The interval of the frequency between the structure and exciting vibration frequency should be greater than 20~30% in operating condition according to *pump station design specification (GB50265-2010).*The expression is as follow [4]:

$$\frac{(f_i - f_{0i})}{f_i} \times 100\% > 20\% \sim 30\% \quad \text{or} \quad \frac{(f_{0i} - f_i)}{f_{0i}} \times 100\% \geq 20\% \sim \tag{1}$$

Where, f_{0i} is the ith order vibration frequency of the structure, f_i is the frequencies of vibration sources of various equipment.

The vibration of pump station structures mainly results from machines, electromagnetism and hydraulic vibration which have relation to rotation frequency of the pump and close to its rotational frequency. In this project, the rotational frequency of the pump is 3.575 Hz. The ±20% of the rotational frequency ranges between 2.86 and 4.29 Hz. The frequency of the whole structure system is beyond the range both in completion and operating conditions.

Transient vibration analysis

Numerical method

The unsteady flow in the passageway was simulated using the RNG $k-\varepsilon$ model [5]. The pressure-velocity coupling was performed using the SIMPLEC algorithm. Second-order format was used for pressure term [6]. 5000 time steps were picked out, with time step as 0.01s in transient analysis.

There were three combinations of boundary condition used in pump flow analysis. (1) Inlet: according to the previous research, the predominant frequency of the pulsating pressure in passageway is close to the rotational frequency and unevenness of the pulsating pressure is in the range of 16%. Therefore, a simple harmonic velocity, $v=\bar{v}(1\pm 0.1\sin wt)$, with $\bar{v}$ =0.865 m/s, pulsation amplitude of 10% and pulsation frequency being equal to rotational frequency, was specified at the inlet[7] [8][9][10]. A averaged velocity, $\bar{v}$ =0.865m/s, is obtained based on designed single unit flow 14.3 m^3/s and area of the inlet of the pump station. (2) The vent was set as outflow boundary condition [11] [12]. (3) The SFI boundary was set in interface between the steel passageway and fluid.

Concrete structure vibration

The vibration amplitude of the displacement and stress of key points in the concrete structure are listed in Table 4 and 5. The positions of the key points were shown in Fig. 9.

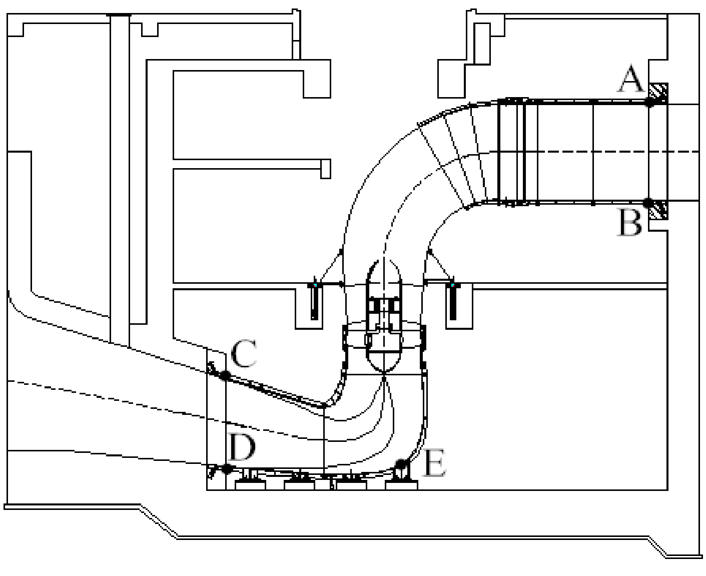


Figure 9. Key points in the concrete structure

The vibration displacement of key points is tiny. The maximum X-direction vibration amplitude of displacement is 0.019 um in the concrete supports in the elbow of the passageway. The maximum Y-direction and Z-direction vibration amplitude of displacement is 2.311 and 3.046 um respectively, and both in the joint between the concrete inlet and steel passageway. The vibration amplitude of stress of all key points is much smaller than strength of the concrete, which is not the controlling factor in the concrete structure design.

Table 4. The amplitude of the vibration displacement of the key points in the concrete structure in operating condition（μm）

Key point	Amplitude of vibration displacement		
	X-direction	Y-direction	Z-direction
A	0.004	1.390	0.176
B	0.002	1.064	0.199
C	0.002	2.311	3.046
D	0.004	0.945	0.038
E	0.019	0.864	0.004

Table 5. The amplitude of the vibration stress of the key points in the concrete structure in operating condition（kPa）

Key points	Normal stress amplitude			Amplitude of the first principal stress	Amplitude of the third principal stress
	σ_x	σ_y	σ_z		
A	1.327	0.385	3.245	2.409	1.326
B	1.388	0.349	4.094	1.388	4.064
C	4.391	0.521	10.492	1.921	11.991
D	0.176	0.200	0.033	0.598	0.448
E	1.919	0.851	0.226	1.946	0.703

Steel passageway vibration

The vibration amplitude of the displacement and stress of key points in the steel passageway were list in Table 6 -8. The positions of the key points were shown in Fig. 10.

The vibration amplitude of displacements of key points in the steel passageway is also tiny.

The maximum X-direction vibration amplitude of displacement is 31.520 um in Point 2 in the side wall of the inlet segment of the passageway. The maximum Y-direction and Z-direction vibration amplitude of displacement are 53.215 and 176.435 um respectively, and both in Point 1 in the top surface of the inlet segment of the passageway. The vibration amplitude of stress of all key points is much smaller than strength of the steel, which is not the controlling factor in the steel passage design.

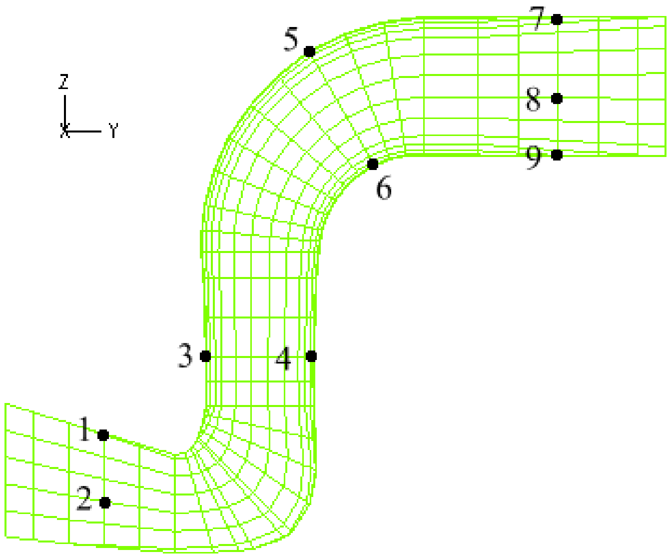


Figure 10. Key points in the steel passageway

Table 6. The amplitude of the vibration displacement of the key points in steel passageway in operating condition（μm）

Key point	Amplitude of vibration displacement		
	X-direction	Y-direction	Z-direction
1	0.008	53.215	176.435
2	31.520	3.879	0.606
3	0.013	12.045	1.282
4	0.014	4.382	0.755
5	0.040	1.192	0.371
6	0.024	1.654	2.103
7	0.012	1.389	6.322
8	4.518	1.394	0.388
9	0.014	1.106	7.791

Table 7. The amplitude of the normal stress of the key points in steel passageway in operating condition（kPa)

Key point	Normal stress amplitude		
	σ_x	σ_y	σ_z
1	298.000	282.660	19.909
2	1.958	301.050	398.900
3	358.400	2.268	33.386
4	767.900	4.967	46.750
5	17.750	18.332	6.875
6	69.215	37.165	9.418
7	120.634	58.260	0.005
8	1.598	21.142	57.662
9	140.634	75.242	0.009

Table 8. The amplitude of the shear stress and principal stress of the key points in steel passageway in operating condition（kPa)

Key point	Shear stress amplitude			Amplitude of the first principal stress	Amplitude of the third principal stress
	τ_{xy}	τ_{xz}	τ_{yz}		
1	0.486	0.165	75.480	302.850	0.230
2	24.329	1.816	47.720	418.350	0.019
3	0.066	0.969	0.566	33.317	358.400
4	0.014	0.197	2.738	46.910	767.900
5	0.190	0.091	11.331	25.247	17.750
6	0.478	0.288	18.067	0.710	69.220
7	0.337	0.172	0.594	58.287	0.095
8	3.472	4.582	15.371	46.237	39.900
9	0.238	0.016	0.424	0.429	140.631

Vibration safety assessment

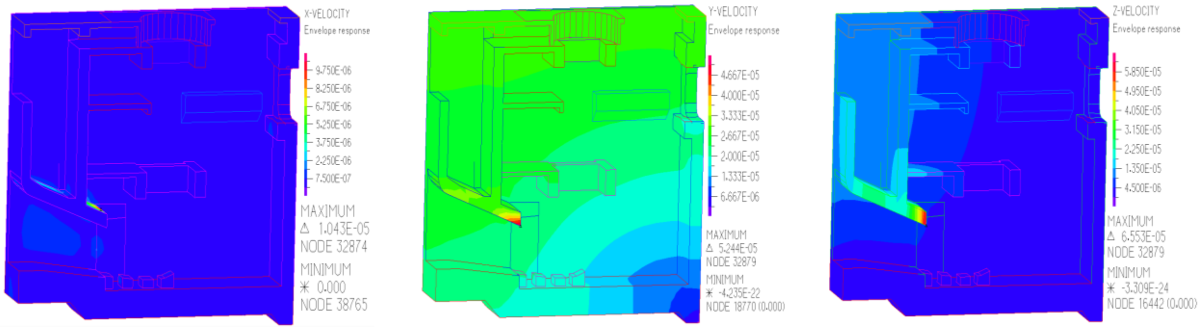
At present, there is no explicit control standard for the vibration checking of pump station structures in China. The vibration of pump station structures is long-term continuous forced vibration, which is similar to the vibration of the hydropower house. Major research focused on the vibration control standard for hydropower house. The suggested vibration control standard for hydropower house is proposed, as shown in Table 9 [5]. The vibration of this pump station is assessed based on the standard for hydropower house.

Table 9. Suggested vibration control standard for hydropower house

Structure member		Vibration displacement (mm)	Vibration velocity (mm/s)		Acceleration (m/s^2)	
			Vertical	Horizontal	Vertical	Horizontal
Floor	As general structure	0.2	5.0		1.0	
	As instrument foundation	0.01	1.5			
	Human health	0.2	3.2	5.0	0.4	1.0
Solid wall		0.2	10.0		1.0	
Generator pier		0.2	5.0		1.0	

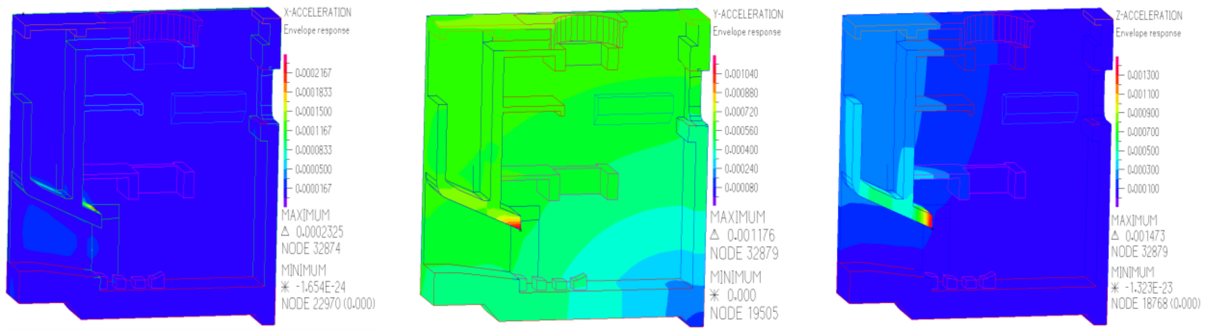
The maximum vibration amplitude of the concrete structure and steel passageway including displacement, velocity and acceleration are list in Table 10-12. The Envelope diagrams of vibration responses are shown in Fig. 11 to 14.

Compared the data in Table 10-12 with the suggested standard in Table 9, the amplitude of vibration displacement of whole pump station system is not large. The amplitude of vibration displacement of concrete structure belongs to the allowed value listed in Table 9. The amplitude of vibration displacement in top surface of the inlet section of the steel passageway is 0.176mm. It should be relieved by strengthening stiffening ribs. The vibration velocity of the concrete structure belongs to the allowed value listed in Table 9. The maximum Z-direction vibration velocity of the steel passageway is 3.765mm/s, exceeding the index of human health (3.2mm/s). There is no office area near the passageway, so it is available. The vibration acceleration of the concrete structure and steel passageway belong to the allowed value listed in Table 9.



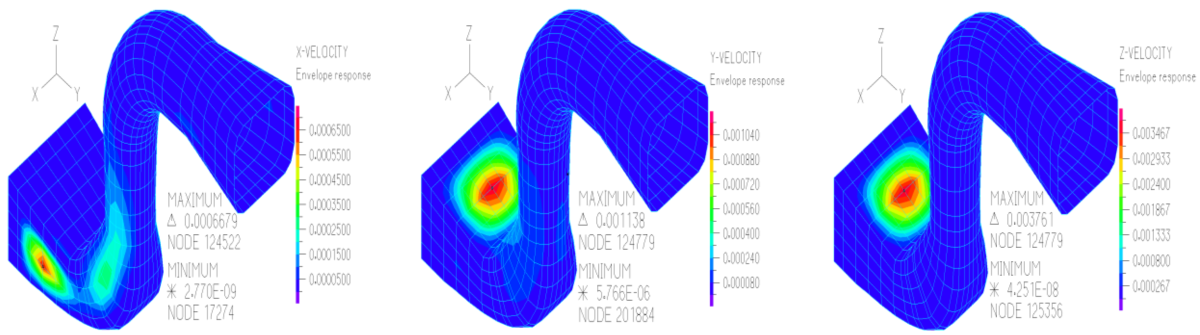
(a) X-direction **(b) Y-direction** **(c) Z-direction**

Figure 11. Envelope diagram of the vibration velocity of the concrete structure (m/s)



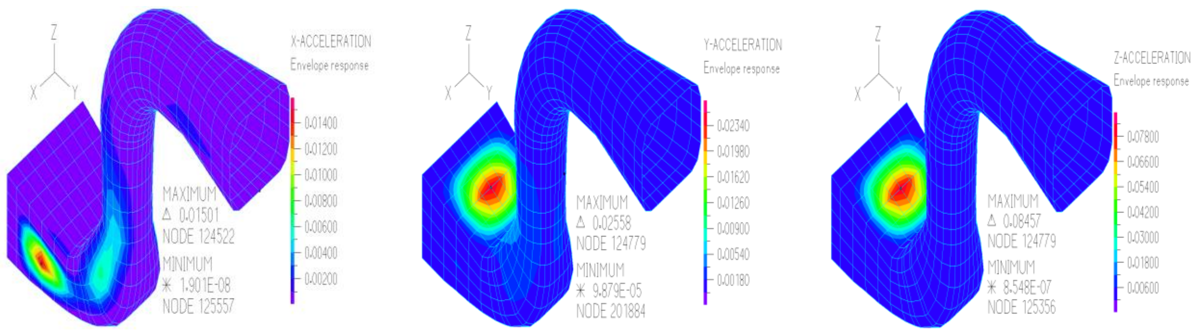
(a) X-direction **(b) Y-direction** **(c) Z-direction**

Figure 12. Envelope diagram of the vibration acceleration of the concrete structure (m/s^2)



(a) X-direction **(b) Y-direction** **(c) Z-direction**

Figure 13. Envelope diagram of the vibration velocity of the steel passageway (m/s)



(a) X-direction **(b) Y-direction** **(c) Z-direction**

Figure 14. Envelope diagram of the vibration acceleration of the steel passageway (m/s^2)

Table. 10 The maximum vibration amplitude of displacement（μm）

	X-direction	Y-direction	Z-direction
Concrete structure	0.019	2.311	3.046
Steel passageway	31.520	53.215	176.435

Table. 11 The maximum vibration velocity（mm/s）

	X-direction	Y-direction	Z-direction
Concrete structure	0.010	0.052	0.066
Steel passageway	0.067	1.139	3.765

Table. 12 The maximum vibration acceleration（m/s^2）

	X-direction	Y-direction	Z-direction
Concrete structure	0.0002	0.001	0.001
Steel passageway	0.015	0.025	0.085

Conclusion

(1) The water filling in the passageway has obvious effects on the vibration characteristics of the whole pump station system. The fluid-structure interaction is essential factor in resonance check of the pump station structure system.

(2) The flow-excited vibration of the pump station is tiny and high frequency. The joint between the concrete inlet and steel passageway and the top surface of the inlet of the steel passageway are weakness positions where should be strengthened in design.

(3) A FSI model considering the interactions of the concrete structure with steel passageway, fluid and pump machinery should be established and investigated.

Acknowledgement

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