Numerical simulation of dynamic characteristics of radial gates considering the effect of the pier

Jiliang Liu [1], Honglin Xi [1], Zheng Si [1], Xurong Dong [2]

[1]College of Water Resources and Hydropower Engineering, Xi'an University of Technology, Shaanxi, Xi'an 710048, China
[2]Shaanxi Province Institute of Water Resources and Electric Power Investigation and Design, Shaanxi, Xi'an 710001, China

Corresponding author: XI Honglin, E-mail:1730939969@qq.com

Abstract. Radial gates play an important part in the comprehensive benefit of hydropower stations. Failures of radial gates are usually related to their dynamic characteristics. To appropriately evaluate the dynamic characteristics of the radial gate, the effect of the pier should be considered. In this paper, a reasonable finite element model of the radial gate-pier system was established, and the dynamic characteristics of the radial gate were calculated. The effect of the pier on the natural frequency and mode shape of the radial gate was studied. The results show that the pier has a great influence on the mode shape of the radial gate arm and panel, and the natural frequency of the radial gate decreases considering the effect of the pier.

Keywords: Radial gate-pier system; dynamic characteristics; finite element analysis

1 Introduction

With the rapid development of water conservancy and hydropower in China, a large number of hydraulic structures with high heads have been designed and built one after another. Metal structures are indispensable for the normal operation of hydraulic structures, among which radial gates are widely used in water conservancy hubs due to their advantages such as being able to close a considerable aperture, low opening and closing force, and no gate slot. It is usually used as a working gate and is the regulating structure of water conservancy hubs. The safe operation of the radial gate is an important guarantee for the comprehensive benefits of water conservancy hubs [1].

Failures of radial gates are often related to their dynamic characteristics. When the frequency of flow is close to the nature frequency of a certain order of the radial gate, it will cause severe vibration (so-called resonance), which will affect the normal operation of the radial gate, and may even cause instability and damage. Some damage examples are listed in Table 1. The finite element method is usually employed to establish a numerical simulation model to calculate the dynamic characteristics of radial gates

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Many researchers focused on the numerical simulation of the dynamic characteristics of radial gates [2-10]. The radial gate is connected to the pier as a system. Therefore, the dynamic characteristics of the radial gate are affected by the pier. In this paper, a reasonable finite element model of the radial gate-pier system was established to compute the dynamic characteristics of the radial gate. Besides, the effect of the pier on the dynamic characteristics of the radial gate was analyzed.

Table 1. Failures of radial gates

Project Name	Reason of failures
Gates of the Arkansas Canal	The poor bottom edge of the gate
Radial Gate of Barkley Dam	Submerged by tailwater
Radial gate of Baoji Gorge	Severe vibration occurs when partially opening
Radial gate of Sanyizhai Hydropower Station	The loss of dynamic stability
Radial gate of Hedi Reservoir	Impact jet at the bottom of the breast wall
Radial gate Ganxi Hydropower Station	Friction and vibration of support hinges
Radial gate of Miyun Reservoir	Flow-induced vibration

2 Governing equation of mode analysis

According to the principle of structural vibration, the differential equation of motion for a vibration

A system composed of a multi-degree-of-freedom structure can be expressed as:

$$[\boldsymbol{M}_s]\{\ddot{\boldsymbol{u}}\}+[\boldsymbol{C}_s]\{\dot{\boldsymbol{u}}\}+[\boldsymbol{K}_s]\{\boldsymbol{u}\}=\{\boldsymbol{F}\} \tag{1}$$

where **[*Ms*]** is the mass matrix; **[*Cs*]** is the damping matrix; **[*Ks*]** is the Stiffness matrix, $\ddot{\boldsymbol{u}}$ 、 $\dot{\boldsymbol{u}}$ and $\boldsymbol{u}$ are acceleration, velocity, and displacement, respectively. ***Fs*** is the column vector of the excitation force. If one wants to obtain the free vibration equation of the structure, let **{*F*}**=0.

The impact of damping on the vibration characteristics of gate systems in practical engineering is minimal. Therefore, simplify Equation (1):

$$[\boldsymbol{M}_s+\boldsymbol{M}_p]\{\ddot{\boldsymbol{u}}\}++[\boldsymbol{K}_s]\{\boldsymbol{u}\}=0 \tag{2}$$

Under specific initial conditions, the gate structure will undergo simple harmonic motion, so the solution of Equation (2) can be assumed as:

$$\{u\}=\{\phi\}\sin(\omega t+\varphi) \tag{3}$$

Substituting Equation (3) into Equation (2) and considering the arbitrariness *sin(ωt+φ)*:

$$\left([\boldsymbol{K}_s]-\omega^2[\boldsymbol{M}_s]+[\boldsymbol{M}_p]\right)\{\phi\}=0 \tag{4}$$

When the structure undergoes free vibration, the amplitudes of each node in Equation (4) are not all 0. Therefore, the determinant value of the matrix in parentheses in Equation (4) must be equal to 0. Therefore, the equation that the natural frequency of the gate structure satisfies is:

$$\left|\left[\boldsymbol{K}_s\right]-\omega^2\left[\boldsymbol{M}_s\right]+\boldsymbol{M}_p\right|=0 \tag{5}$$

Expanding Equations (5) yields information about ω The nth-degree algebraic equation with positive and negative coefficients of 2, that is, the natural frequency equation, is solved to obtain the n frequencies of the gate structure, which are arranged in the order from small to large as ω_1, ω_2, ω_3, … ω_n and obtain the 1st, 2nd, 3rd..., nth natural frequencies of the gate structure.

3 Finite element model

Taking the radial gate of a certain water conservancy project as an example, the bottom elevation of the gate chamber is 326 meters, the normal water storage level is 334.5 meters, and the check water level is 337 meters. The pier thickness is 4.0 meters and the pier height is 25 meters. The gate size is 12.0 m × 12.9 m (width × Height), and the arm length of the radial gate is 15.5 m. Each gate has a total of 2 main beams, 6 longitudinal beams, and 14 secondary beams. Using a dual lifting point hydraulic hoist for opening and closing.

The radial gate belongs to a thin-walled spatial structure, so all structures except for the support hinge are simulated using the shell element shell181 element; Solid185 was used to simulate the support hinge, hinge seat, gate pier, gate bottom plate, and bracket. The specific model is shown in Figure 1. Specific parameters are shown in Table 2.

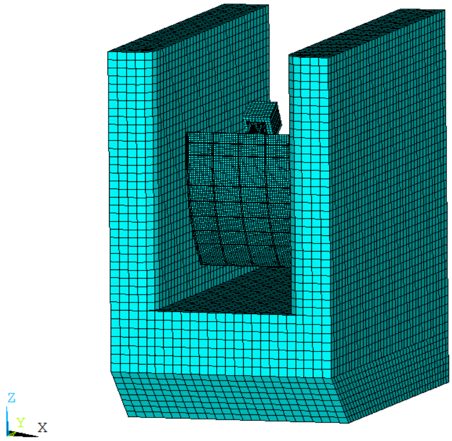


Fig. 1. Finite element model

Table 2. Physical and mechanical parameters of each component

Component Name	Material quality	Elastic modulus/MPa	Poisson's ratio	Density (kg/m^3)
Radial gate	Q235B	206000	0.3	7850
Hinge	Cast steel ZG310-570	210000	0.27	7850
Gate pier	C25 reinforced concrete	25500	0.167	2500
Bracket	C30 reinforced concrete	30000	0.167	2500
Gate seal	Rubber	10	0.499	1500

4 Results and discussion

4.1 Natural frequency analysis

The Lanczos method was used to solve the natural frequency of the gate structure, without considering the influence of fluid-structure coupling. Modal analysis of the single model of radial gate and pier system models are carried out respectively. The high-order vibration mode of the radial gate is mainly reflected in the vibration of components such as longitudinal beams and crossbeams, while local vibration does not pose a threat to the stability of the overall structure. The low-order vibration is mainly manifested in the overall vibration of the gate panel and support arm, with a low frequency, which is close to the main pulsation frequency range of water flow. Therefore, this study only takes the first 10 natural vibration frequencies of the radial gate, and the specific frequencies of each order are shown in Figure 2.

From Figure 2, the modes of the single-body model of the radial gate and the radial gate pier system model are relatively concentrated. The frequency of the single-body mode of the radial gate is between [0, 5] Hz, while the mode of the radial gate pier system is in [0, 3] Hz. The natural frequencies of both models are relatively dense, with the 4th and 5^{th}-order natural frequencies of the individual model being the same, while the 7th and 10^{th}-order natural frequencies of the system model only differ by 0.102 Hz. The natural frequencies of the system model have decreased compared to the single body model of the radial gate, with the 4th order frequency decreasing the most, with a frequency decrease of up to 57.58%. The first-order frequency has the least reduction, only 0.34%. From the calculation results, the natural frequencies of the single body and pier system models of the dry mode radial gate without considering fluid-structure coupling are Relatively dense, and even the adjacent natural frequencies are completely the same.

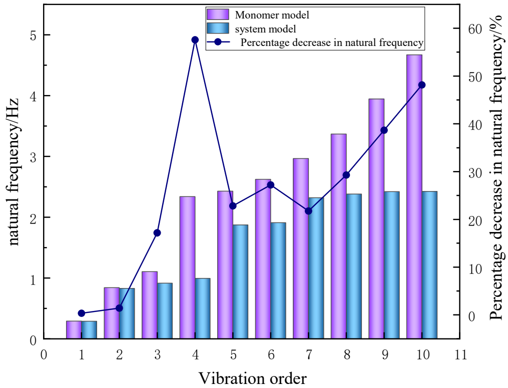


Fig. 2. Dry mode natural frequencies of each order

The pier has a significant impact on the low-order natural frequencies of the radial gate, while it has a relatively significant impact on the higher-order natural frequencies of the radial gate.

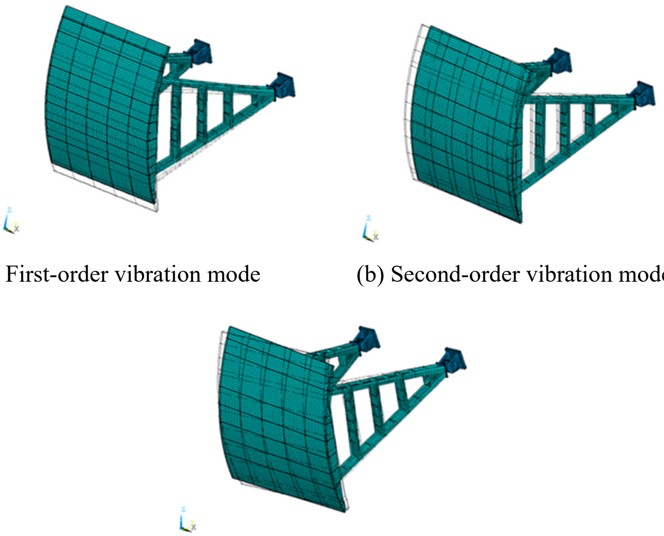
4.2 Vibration mode analysis

The natural vibration characteristics of the radial gate change with the change of gate opening and the vibration characteristics of the system model are also affected by the gate pier compared to the single-body model. This paper selects the first 5 vibration modes of the radial gate for research, and after sorting, extracts the first 5 vibration modes of the overall structure of the gate. The corresponding vibration mode results are shown in Table 3.

Table 3. Vibration mode result

Order	Monomer model	System model
1	Vertical vibration of the support arm	Vertical vibration of the support arm
2	Overall left and right vibrations	Overall left and right vibrations
3	Overall Torsional vibration	Overall Torsional vibration
4	Reverse vibration of the support arm	Overall Torsional vibration
5	Left and right vibrations of longitudinal beams	Panel Torsional vibration

From the calculation results of the dry mode radial gate single body model and the radial gate pier system model, the vibration modes of the single body model and the system model are different in the anhydrous state. The vibration patterns of the single-body model and the system model are the same in the first three orders, while the vibration patterns of the 4th to 6th orders are different. The fourth order of the single body model mainly focuses on the vibration of the radial gate arm, while the 5th to 6th orders are both the left and right vibrations of the longitudinal beam of the meeting gate; the 4th to 5th orders of the system model mainly focus on the overall vibration of the panel and radial gate. The vibration mode diagram of the system model is shown in Figure 3.



(a) First-order vibration mode (b) Second-order vibration mode

(c) Third-order vibration mode

Fig. 3. Dry mode vibration mode of the system model

5 Conclusion

The effect of the pier on the dynamic characteristics of the radial gate was analyzed in this paper by numerical simulation and the conclusions are as follows:

(1) Considering the influence of gate piers, the natural vibration frequency of the radial gate becomes smaller and denser, and the maximum decrease in natural frequency of the radial gate under dry mode is 57.58%

(2) The pier has a significant impact on the vibration mode of the radial gate. Considering the impact of gate piers on the intensified vibration of the radial gate arm, it is necessary to consider
strengthening and optimizing the radial gate

(3) The radial gate-pier system model can more accurately reflect the vibration situation of the radial gate, which is more like the actual situation

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