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Acoustic resonance analysis of new water drop labyrinth control valve for thermal power units

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Abstract: *In order to study the acoustic resonance effect of a new type of water drop labyrinth regulating valve, the structural modal information and flow field information of the regulating valve under typical operating conditions are calculated by using ANSYS; Then the distribution characteristics of flow-induced noise of the regulating valve are calculated by using LMS software and acoustic boundary element method. The results show that the minimum structural natural vibration frequency of the regulating valve is 133.29 Hz; The noise distribution of the valve is low frequency, and the maximum flow-induced noise can reach 142 dB, and the main frequency of the noise generated is 60 Hz~125 Hz; Therefore, according to the structural resonance conditions of the valve, the new water drop labyrinth regulating valve will not produce acoustic resonance due to flow-induced noise.*

Keywords: *Modal information; Noise; Frequency; Acoustic resonance*

1. Introduction

Labyrinth regulating valve is widely used in thermal power units and industrial fluid control pipeline systems due to its advantages of good pressure reduction performance, good flow resistance characteristics, and ability to adapt to the harsh working conditions of high temperature and high pressure. However, when labyrinth regulating valve is used in ultra-(ultra-) critical thermal power units, it is lack of noise, vibration and other problems. The medium of ultra (ultra) critical thermal power unit is in the critical coexistence state of gas-liquid two phases during operation. When the medium flows through the throttle of the valve, the severe pressure fluctuation will cause cavitation effect, resulting in noise, vibration and other problems. In response to this problem, the research team proposed a new type of water drop labyrinth control valve applied to the ultra-critical thermal motor. The previous research shows that the flow characteristics, flow resistance characteristics, pressure pulsation and other fluid characteristics of the control valve with this structure are significantly better than the existing labyrinth control valve. This paper will further study its characteristics in noise, vibration and other aspects [1-3].

At present, relevant scholars have carried out research on the noise and vibration generated by the control valve. For example, Hou Congwei analyzed the acoustic response characteristics of the sleeve structure parameters to the orifice sleeve control valve using CFD method and aerodynamic noise theory, and proposed a noise reduction structure design scheme, with good noise reduction effect [4]; Meng Xiangrui used ANSYS to analyze the flow field characteristics of the multistage step-down regulating valve, and calculated the main frequency band distribution of its noise. The maximum sound pressure level of its monitoring point is 140 dB [5] in the range of 180 Hz to 220 Hz; Wen Jun and others used theoretical analysis and ANSYS to study the flow-induced vibration characteristics of low-temperature regulating valve, determined that periodic fluid impact caused the vibration of the valve, and put forward optimization measures [6]. However, most of the current research is focused on individual noise or vibration, without considering the possible impact of the noise frequency characteristics of the structure on the valve body structure; Therefore, this paper will comprehensively analyze the structural natural vibration characteristics and acoustic frequency of the new type of water drop labyrinth regulating valve, and further study the acoustic resonance problem that may be caused by the noise of the regulating valve.

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2. Theoretical basis of analysis

2.1 Modal analysis theory

The dynamic equation of the mechanical structure system in undamped free vibration is:

$$[M]\{\ddot{u}\}+[K]\{u\}=\{0\} \tag{1}$$

Where, [M] and [K] are the total mass matrix and total stiffness matrix of the structure[7,8] respectively; Is the acceleration of each unit node, in m/s-2; {u} Is the displacement of the element node, in m. Under the determined external load, the motion of the structural system is simple harmonic vibration, and the displacement of the element node is:

$$\{u\}=\{u\}\sin(\omega t+\theta) \tag{2}$$

Due to sin (ω t+ θ) The phase angle of is arbitrary, and the simplified formula (2) into formula (1) can be obtained:

$$([K]-\omega^2[M])\{\varphi\}=\{0\} \tag{3}$$

Therefore, the vibration characteristic equation of the system can be expressed by the following formula:

$$\left|[K]-\omega^2[M]\right|=0 \tag{4}$$

The eigenvalue of the equation can be obtained by the above formula ω_{i}, ω_j is the natural frequency.

2.2 Noise calculation model

The noise generated by the water droplet labyrinth regulating valve can be calculated and solved using computational aviation acoustics, which is based on Lighthill's acoustic analogy equation, which is obtained through the N-S equation [9]. The continuity equation and momentum equation of the N-S equation can be written as follows:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0 \tag{5}$$

$$\rho\left(\frac{\partial u_i}{\partial t}\right)=\frac{\partial p}{\partial x_i}+\frac{\partial\tau_{ij}}{\partial x_i} \tag{6}$$

Where τ_{ij} is the viscous stress tensor, which can be obtained by combining Formula (5) and Formula (6):

$$\frac{\partial\rho u_i}{\partial t}+c_0^2\frac{\partial\rho}{\partial x_i}=\frac{\partial T_{ij}}{\partial x_j} \tag{7}$$

Where c0 is the velocity of sound, and Tij is the turbulent stress tensor of Lighthill, which can be expressed in the following form:

$$T_{ij}=\rho u_i u_j+\delta_{ij}\left[(p-p_0)-c_0^2(\rho-\rho_0)\right]-\tau_{ij} \tag{8}$$

Where ρ_0 and p_0 are the atmospheric density and pressure, respectively. The relationship between the continuity equation and time is distinguished by formula (5), and then the divergence of formula (7) is taken, and then the result is subtracted to obtain the acoustic analogy equation of Lighthill:

$$\frac{\partial^2\rho`}{\partial t^2}-c_0^2\frac{\partial\rho`}{\partial x_i x_j}=-\frac{\partial^2 T_{ij}}{\partial x_i x_j} \tag{9}$$

ρ′ Is the change of sound density, ρ′=ρ-ρ 0.

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3. Analysis model establishment

The new type of water droplet labyrinth regulating valve is mainly composed of valve body, water droplet disc, disc pressing sleeve, and other parts. Its three-dimensional model is established using Solidworks software, as shown in Fig.1. The arrow in the Fig.represents the flow direction of the medium; In order to avoid the stress singularity and improve the calculation accuracy, the pipe with 5 times the pipe diameter length is added during modeling. Compared with other regulating valves, the key point of the new type of water drop labyrinth regulating valve is that the regulating elements of the valve core are different. The structure of the valve core disc is shown in Fig.2. Each stage disc contains 8 flow channels, which are composed of several water drop shaped protrusions. According to the principle of noise generation, the greater the pressure drop in a short distance, the greater the pressure pulsation, and the greater the noise generated. Therefore, this paper only studies the acoustic resonance relationship between the noise and the structure at a small opening, and its operating parameters are shown in Table 1.

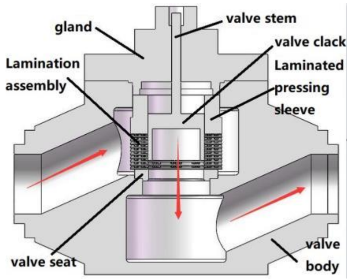

Figure 1: Profile diagram of water droplet labyrinth valve

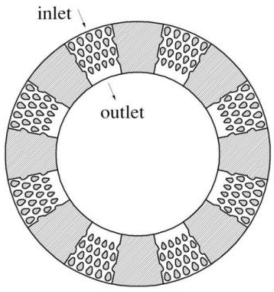

Figure 2: Structure of water droplet maze disk

Table 1: Working Condition Parameters of Water Drop Labyrinth Regulating Valve

Type	Operating condition opening	Inlet pressure/MPa	Outlet pressure/MPa	temperature/℃	medium
Value	22%	16.9	0.9	110	water

In Solidworks, the internal flow channel model is obtained by reverse modeling, and then the model is imported into the ANSYS MESH module. The adaptive method is used to divide the grid, and the outlet flow quality is used as the grid independence judgment parameter. The results are shown in Fig.3 and Fig.4. Finally, 930620 nodes and 4171535 grids are determined, and the average grid quality is 0.82.

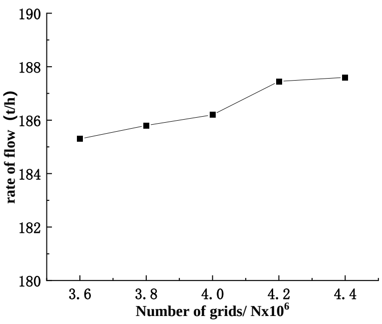

Figure 3: Grid independence verification

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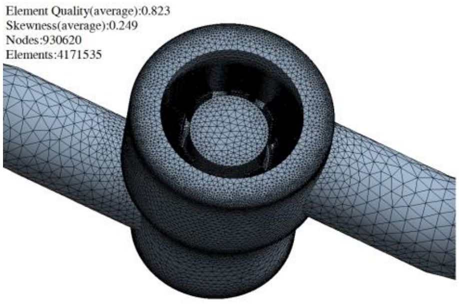


Figure 4: Grid division results

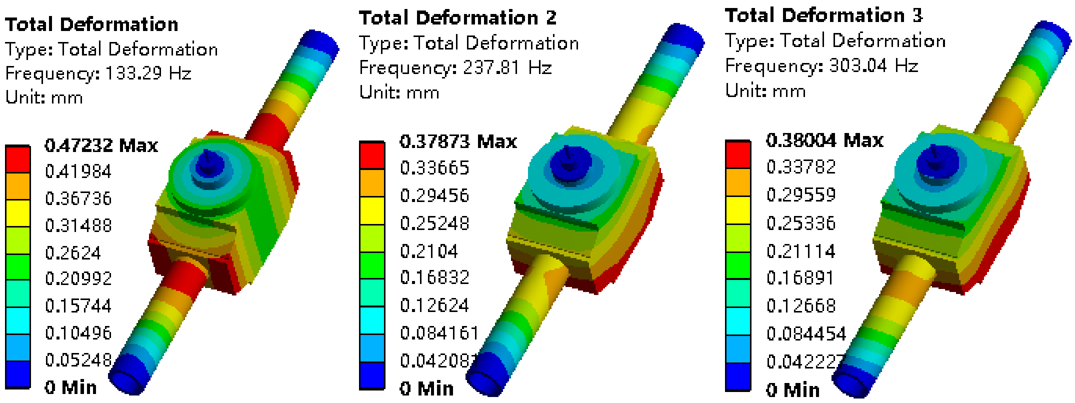
4. Acoustic resonance analysis

4.1 Modal analysis

Use ANSYS Modal module for modal analysis, import the established 3D model into Geometry for processing, and repair some damaged surfaces; then, the adaptive mesh division technology is used to divide the mesh, control the overall maximum cell size not to exceed 20 mm, and locally densify the valve core assembly. This modal analysis adopts non-prestressed module analysis, adds constraints according to the actual installation position, applies fixed constraints on both ends of the pipeline, and applies displacement constraints on the bottom of the valve body and the top of the valve stem, respectively limiting their displacement in the vertical and horizontal directions. The practical application of the project is more concerned with the low order frequency of the structure. Therefore, the maximum number of solving steps is set to 20. According to the above settings, the modal information of the water drop labyrinth control valve is obtained by solving as shown in Table 2. Only the first 10 steps are given in the text; In order to further analyze the vibration characteristics of the water drop labyrinth regulating valve, the first three modal vibration modes are extracted as shown in Fig.5.

Table 2: The first 10 modal information of water drop labyrinth regulating valve

Order	Frequency/Hz	Order	frequency/Hz
1	133.29	6	496.27
2	237.81	7	518.47
3	303.04	8	748.16
4	471.57	9	784.21
5	475.5	10	826.77



(a) first order *(b) second order* *(c) 3rd order*

Figure 5: Vibration mode of water drop labyrinth regulating valve (first 3 steps)

According to Table 2 and Fig.5, the lowest modal frequency of the water drop labyrinth regulating valve is 133.29 Hz, and the frequency increases rapidly with the increase of order; In addition, at low frequency, the vibration of the valve is mainly concentrated near the joint between the pipe and the valve body[10][11].

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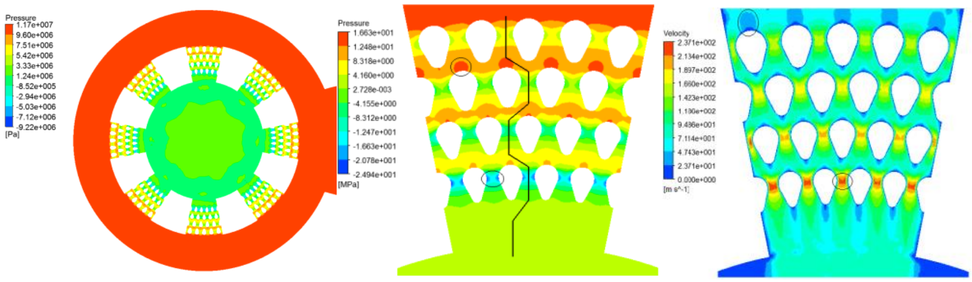
4.2 Flow-induced noise analysis

4.2.1 Flow field information calculation

FLUENT and LMS software are used to jointly calculate the flow-induced noise of the water drop labyrinth regulating valve. First, FLUENT software is used to calculate the flow field characteristics of the water drop labyrinth regulating valve, including pressure pulsation, vortex, etc; then the flow field pressure information is imported into LMS software, and the flow-induced noise of the water drop labyrinth control valve is calculated and solved. When calculating the flow field, the steady state solution is adopted first, and the result of steady state convergence is taken as the initial result of transient; The flow field is set as follows: open the turbulence model and hang k- ε Turbulence model; Open the energy equation and set the temperature to 110 ℃; Media types are added according to the actual situation; The inlet and outlet are set as boundary conditions, with an inlet pressure of 16.9 Mpa and an outlet pressure of 0.9 Mpa; Set the convergence residual value to 10-4, and calculate the flow field information according to the above settings; As the disc assembly is the main adjusting element, its pressure change is mainly generated in this part, so only the pressure, velocity and other flow field information of this part are given as shown in Fig.6 [12].



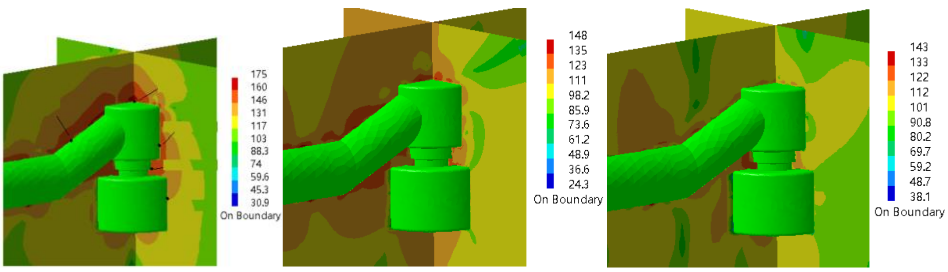
a) Overall pressure *b) Local channel pressure* *c) Local velocity*

Figure 6: Flow field calculation results of water drop labyrinth regulating valve

It can be seen from Fig.6 that the pressure reduction effect of the valve is good, and its pressure changes in gradient with the change of the number of water drops. According to the principle of noise generation, pressure pulsation is the main reason for noise generation. Therefore, in the subsequent noise calculation process, the noise information near the disc assembly will be mainly concerned.

4.2.2 Noise characteristic calculation

The pressure pulsation and other information generated during flow field calculation are imported into LMS software, and the noise characteristics of the water droplet labyrinth control valve are calculated using BEM (Acoustic Boundary Element Method). Because this paper studies the relationship between the flow-induced noise and the natural vibration characteristics of the valve structure, the noise generated by the fluid domain will be directly calculated without considering the influence of the structure when calculating the noise. Firstly, the fluid domain is divided into grids, and the size of the grid is set based on the highest frequency of analysis. Since low frequencies are concerned in engineering applications, combined with the frequency range of control valve noise distribution, the maximum calculation frequency is set to 5000 Hz, so the grid size is 9 mm; Then the calculated pressure information is converted into frequency domain information, and then applied to the grid on the outer surface of the channel; Finally, the noise distribution of the water drop labyrinth regulating valve under the typical frequency is obtained by solving and calculating, and the results are shown in Fig.7 [13].



(a)1000 Hz *(b)3000 Hz* *(c)5000 Hz*

Figure 7: Noise distribution of water drop labyrinth regulating valve

From Fig.7, it can be seen that the water droplet labyrinth regulating valve generates relatively serious noise at the valve core assembly, which is symmetrically distributed. The maximum noise at frequencies of 1000 Hz, 3000 Hz, and 5000 Hz is 174 dB (A), 146.5 dB (A), and 141 dB (A), respectively, indicating that the noise generated is relatively large. In order to further analyze the relationship between its noise frequency and structure frequency, and to determine its dominant frequency distribution, the one-third octave diagram of its part position on the symmetry plane (see Fig.7 (a)) is extracted, and the results are shown in Fig.8.

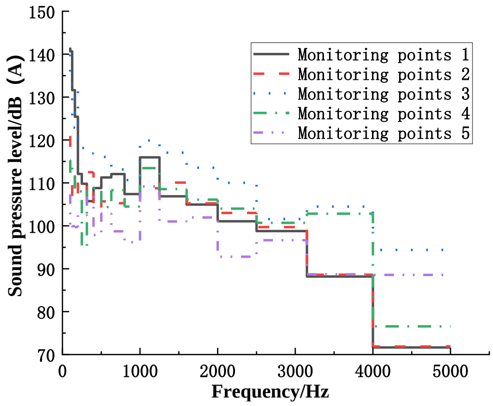


Figure 8: One-third frequency doubling diagram of monitoring points

From the above figure, it can be seen that the noise frequency of the water droplet labyrinth regulating valve exhibits significant low-frequency and broadband characteristics, and the noise distribution at different monitoring points is similar, with higher low-frequency noise and lower high-frequency noise. The maximum sound pressure level of monitoring point 1 is 142 dB (A), and the main frequency range is 100-125 Hz; The maximum sound pressure level of monitoring point 2 is 121 dB (A), and the main frequency range is 75-90 Hz; The maximum sound pressure level of monitoring point 3 is 139 dB (A), and the main frequency range is 100-120 Hz; The maximum sound pressure level at monitoring point 4 is 117 dB (A), and the main frequency range is 70-85 Hz; The maximum sound pressure level at monitoring point 5 is 108 dB (A), and the dominant frequency range is 65-75 Hz.

4.3 Acoustic resonance analysis

From the structural modal information and acoustic calculation results of the water droplet labyrinth regulating valve, it can be seen that the minimum natural vibration frequency of the regulating valve structure is 133.29 Hz, and the main frequency of the noise generated is distributed between 60-125 Hz. Therefore, the water droplet labyrinth regulating valve will not generate acoustic resonance due to flow noise; however, their frequencies are relatively close, which may aggravate the vibration of the structure itself. Further analysis of the calculation process shows that the impact of the actuator on the valve is not considered in the modal analysis. In the actual use process, the actuator will improve the rigidity of the water drop labyrinth regulating valve, thus increasing its modal frequency. To sum up, the water drop labyrinth regulating valve will not produce acoustic resonance due to flow-induced noise during use.

5. Conclusion

In order to study the acoustic resonance effect of the new type of water drop labyrinth regulating valve, this paper uses ANSYS and LMS software to simulate and analyze the water drop labyrinth regulating valve. The main conclusions are as follows:

(1) The modal analysis results show that the minimum frequency of the water drop labyrinth regulating valve is 133.29 Hz, and the maximum deformation occurs at the connection position between the valve and the pipeline.

(2) The noise frequency of the water drop labyrinth regulating valve shows obvious low frequency and wide frequency characteristics. The maximum noise generated by it is 142 dB, and the main frequency distribution of each monitoring point is concentrated in 60 Hz - 125 Hz; According to the modal analysis results, the water drop labyrinth regulating valve will not produce acoustic resonance

due to flow noise.

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