Random vibration characteristics of perforated plates in parallel flow

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Abstract. The vibration of perforated plate contains various complex physical phenomena in the fluid field, which is a key issue in fluid-structure interaction. Perforated plates have been widely used in power plants but the flow induced noise and vibration may give arise to some serious adverse impact. Therefore, it is of great significance to clarify the random vibration characteristics and noise problem of perforated plates in parallel flow. In this paper, the perforated plates were experimentally studied in a wind tunnel. Acceleration signal sensors are used to analyze the displacement and deformation of perforated plates and the pressure signals are measured by SETRA C266 micro pressure differential sensor, and the pulsating characteristics of perforated plates are analyzed by fast fourier transform (FFT), respectively. Through the analysis, it is found that the main pressure fluctuations of the flow direction are concentrated in the middle position and the tail. And the pressure fluctuations on the left and right sides of the perforated plates is very close in the spanwise position, and less than the center. Some key factors on the random vibration of perforated plates are discussed including wind velocity, hole diameter, hole pitch, plate thickness and the clearance height between the perforated plate and the cavity (it means back space gap height). The analysis of the results indicated the impact of each factor. In detail, lower wind velocity and smaller hole diameter are beneficial to reduce the random vibration of perforated plate, however, larger hole pitch size and larger plate thickness are favorable to reduce the random vibration. The test results of this paper can provide a basis for the design of perforated plates.

Key words: Perforated plate, RMS, pressure fluctuations, random vibration

1. Introduction
At present, perforated plates has found an increasingly wide utilization in engineering field, and they are not only used for sorting and screening materials, as well as Heating, Ventilating and Air Conditioning (HVAC), sound insulation and so on. At the same time, perforated plates are also widely used in power plants, which are mainly used to control flow and reduce pressure. Perforated plates
vibrations are caused by fluid force. The fluid forces are classified into a cross flow and a parallel flow. For example, self-excited vibration of baffle plates in a heat exchanger occurs by the cross flow and random vibration of silencers in a plant duct is excited by the parallel flow.

For a long time, scholars at home and abroad have done a lot of research on the interaction between cross flow and perforated plates. By simplifying the model of the perforated plate and using the empirical correlation, Guo B Y, Hou Q F, et al. [1] predict the distribution of the fluid from microscopic to macroscopic. They mainly studied the causes of flow structure and pressure loss, and verified the feasibility of using the perforated plate to control fluid flow. In order to effectively suppress liquid sloshing in the liquid storage tank and prevent the damage of the tank. Jin H and Liu Y, etc. [2] has designed a horizontal perforated plate to improve energy dissipation and reduce the force of the liquid on the structure. This study shows that the horizontal perforated plate can effectively suppress the violent resonance produced by the liquid sloshing in the rectangular groove under the horizontal excitation. Jhung M J and Jeong K H [3] use finite element analysis to verify the validity of effective modulus of elasticity of rectangular plates with square holes, and put forward a theoretical method for calculating the natural frequencies of semi perforated square plates with fixed edges.

However, there are few scholars studying the interaction between parallel flow and perforated plate. For now, it is not clear that the random vibration characteristics of parallel flow and perforated plate are caused by the interaction between them. Therefore, it is of great significance to determine the random vibration mechanism of the perforated plate in the parallel flow and to determine the fluid excitation force. Nekomoto Y and Nishimura M, et al. [4] studied the horizontal and relevant area of pressure fluctuation through wind tunnel test. They compare the numerical simulation analysis with the experimental results and confirm the correctness of the evaluation method. Slot T and O’Donnell W J [5] studied the relationship between effective elastic constants under different thickness of perforated plate, and the formula for calculating the effective elastic constants of thick perforated plates is derived through the assumption of the generalized plane strain state of thick perforated plates.

The flow of fluid in the cavity below the perforated plates are usually accompanied by vibration, Rowley C W and Juttijudata V [6] used the empirical galerkin model and a simple nonlinear oscillator model to obtain the low order model respectively, which are used to study the oscillatory feedback control technology in cavity flow, and effectively eliminate the oscillation and reduce the amplitude. Ukeiley L S, Ponton M K, et al. [7] studied how to effectively suppress dynamic pressure load in the cavity, which is of great help for reducing the vibration caused by the cavity flow. The mechanism of acoustic coupling in the cavity and pipe is analyzed by Lafon P and Caillaud S, et al. [8] And the phenomenon of cavity noise produced by industrial valves is studied. Meanwhile, through the vibration analysis, they study the energy transfer mode from the fluid to the main pipe, and obtained the solution to suppress or reduce the noise of the valve cavity. Lei J M and Zheng Z W, et al. [9] studied the flow characteristics and pressure coefficient distribution of the cavity, and the results showed that the length-depth ratio was the main factor affecting the flow characteristics of the cavity. Zhang Q F and Li J [10] combined numerical simulation with wind tunnel test to study the flow characteristics of open cavity and the variation of sound pressure level. By analyzing the sound pressure level and frequency diagram, the frequency of different pressure test points in the same mode is the same.

In this paper, wind tunnel tests were carried out by using wind tunnel facilities. Two different measurement methods were used to evaluate the random vibration characteristics of perforated plates. The acceleration signals and fluctuating pressure signals of perforated plates in the parallel flow were measured. The flows are separated by the silencers that consist of perforated plates and acoustic materials. The flows around the perforated plates contain a back flow as well as a surface flow and the fluctuation characteristics are affected by wind velocity, hole diameter, hole pitch, plate thickness, back space gap and so on. Therefore, the flow characteristics are very complicated. We need to focus on the parameters such as the wind velocity, hole diameter and other parameters. Through the analysis of the acceleration signal and pressure fluctuation, the characteristics of random vibration of perforated plates in parallel flow are verified. It provides practical experience for solving the problem of resonant sound absorption in the power plant, and achieved effective result. At the same time, it has a preferably reference value for noise reduction in air conditioners and studios.
2. Experimental setup and data processing

The test wind tunnel is a DC open wind tunnel. The design wind velocities are 5-40 m/s, during the experiment, the main wind velocities $V$ of the wind tunnel were designed to be 10 m/s, 20 m/s and 30 m/s. The test section is a square section of 0.5m*0.5m, and the wind tunnel has good flow performance. Within the design wind velocity range, the turbulence intensity of the experimental section is less than 5 per thousand. The overall layout of the wind tunnel laboratory is shown in Figure 1, and main parameters of the wind tunnel are shown in Table 1.

| Table 1. Main parameters of the wind tunnel. |
|---------------------------------------------|
| Items                                      | Value                                      |
| Test Section Size                          | 0.5 m×0.5 m                                |
| Stable Air Flow Velocity                   | 10-40 m/s                                  |
| Air Flow Stability                         | $\eta \leq 0.6\%$                          |
| Turbulence Intensity                       | $\eta \leq 0.5\%$                          |
| Velocity Homogeneity                       | Velocity homogeneous region is over 85%    |
| Static Pressure Gradient Along Tunnel Axis | $\frac{dp}{dx} \approx 0.01/ m$            |

2.1. Experimental setup

In the measurement of the acceleration signal, we adopted two acceleration sensors, the specific model is Delta-4516. And the sensitivity coefficient is 1.091 mV/ms$^-2$ and 1.045 mV/ms$^-2$, respectively. And the acceleration sensor has a mass of 1.5 g. The pressure signal adopts SETRA C266 differential pressure sensor with different range, which were 25 Pa and 250 Pa, respectively. And the output voltage is 10 V, which is linear distribution. The 1V represents the pressure difference of 2.5 Pa and 25 Pa, respectively. The accuracy is 0.4%, and the sensitivity is 1/10000. NI (BNC-2110) card is used for data collection. The sampling frequency is 5000 Hz, and the sampling time is set to 40 seconds. Data recording software is Dasylab11.0. The system installation schematic is shown in figure 2. Two sensors were calibrated before the experimental data was collected.

2.2. Test model

In this paper, the perforated plates model used in wind tunnel test are shown in figure 3. The total area of the hole net is 530 mm * 430 mm, and the core area of the hole net is 500 mm * 400 mm. In order to minimize the net surface deformation caused by other thermal processing methods, 304 stainless steel is used for one-off punching and forming. The hole network is arranged on the 304 stainless steel frame by welding technology. According to the requirements, the mesh is designed for 7 different combinations of parameters, as shown in table 2. The holes are arranged in staggered arrangement, and the distance between the two holes is the hole pitch, as shown in figure 4.

In order to reduce the influence of the device on the flow field, the head of the bottom support is made into an oval. In the test process, the design scheme of the test model is to adopt the unified bottom support and replace the mesh size. During the test process, ensure that the bottom bracket installation is invariable, and we test the combination of different parameter models only by changing the hole network, adjusting the space between the gap, and assembling by bolt connection in a certain order. The whole CNC processing technology is adopted in the bottom support, the pressure measurement channel is set
inside the bottom bracket. Combining the size and weight of the model, the model material is selected as nylon, which can not only ensure the machining accuracy, but also the quality of the bottom can be controlled. The clearance adjustment plate is used to adjust the size of the gap between the hole network and the bottom, and to arrange the channel for measuring pressure on the clearance adjustment plate. In order to ensure the smoothness of the clearance adjustment plate, the components are selected with aluminum alloy, and the surface is anodized with the whole numerical control molding. The model installation is shown in figure 5. First, the clearance adjustment plate is put into the bottom support and adjusted to the appropriate clearance height, after the adjustment plate is fixed, the hole net is loaded into the bottom support.

### Table 2. Perforated plate parameters.

| Number | Hole diameter $D$ (mm) | Hole pitch $P$ (mm) | Plate thickness $T$ (mm) |
|--------|------------------------|---------------------|-------------------------|
| A1     | 2                      | 5                   | 0.8                     |
| A2 (B2, C2) | 3                  | 5                   | 0.8                     |
| A3     | 4                      | 5                   | 0.8                     |
| B1     | 3                      | 5                   | 0.4                     |
| B3     | 3                      | 5                   | 1.2                     |
| C1     | 3                      | 4                   | 0.8                     |
| C3     | 3                      | 6                   | 0.8                     |

2.3. Test process and data processing

In this paper, the displacement of the perforated plate is reflected by the root mean square (RMS) of the acceleration signal. After preliminarily determining the deformation amount at the location of each monitoring point in the perforated plate, the pressure fluctuation at each monitoring point of the perforated plate is measured. The random vibration characteristics of the perforated plate are more explicit by the size of the displacement and the spectrum of the pressure fluctuation.
2.3.1. The data of the acceleration signal. In order to compare the surface vibration of different hole nets, acceleration sensors are arranged above the hole network and the bottom bracket respectively, as shown in figure 5. The acceleration sensor A is located at the center of the hole net. It is used to measure the vibration of the hole net. The acceleration sensor B is arranged on the bottom bracket to monitor the vibration of the bottom bracket, so as to avoid the error of the experimental result caused by the vibration of the bottom support. Before the test measurement is carried out, the acceleration sensor is attached to the side wall of the wind tunnel to ensure that the vibration during the operation of the wind tunnel will not affect the test results and do the corresponding signal isolation. The results show that the vibration of the side wall of the wind tunnel has no effect on the test results during the operation. In the experiment, the acceleration sensor changes the magnification of the amplifying regulator according to the intensity of the signal to ensure the reliability of the signal measurement. In this paper, the RMS of the acceleration signal are used to analyze the test data of perforated plates. According to the physical meaning of RMS, it represents the effective value of acceleration, while the displacement is the quadratic integral of acceleration, namely, the RSM of acceleration can reflect the deformation magnitude of the plate to a certain extent.

The method for calculating the RMS of acceleration signals is:

\[ x_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} x_i^2} = \sqrt{\frac{x_1^2 + x_2^2 + \cdots + x_N^2}{N}} \]

Where \( x_n \) is the acceleration signal, \( N \) is the sampling period.

2.3.2. Data on pressure fluctuation. As shown in figure 5, five monitoring points are arranged on the stream direction, which are M1-M5, respectively. Three monitoring points are arranged on the cross-stream position, which are L, M3, R, respectively. The time signals of different positions can be measured by installing the micro pressure difference sensor on these monitoring points. The spectral analysis is usually used to analyze the time signal. [11] In this paper, the fast fourier transform (FFT) spectrum method is used to analyze the pressure fluctuation of random vibration of the perforated plate. In spectrum analysis, the amplitude determined by FFT indicates the energy distribution of a time series signal on the frequency. Generally, the transverse coordinates represent the fluctuation frequency of the pulsating pressure, and the ordinate represents the energy of various frequencies in the energy spectrum. A specific frequency corresponding to the highest peak in the spectrogram is called the dominant frequency. The dominant frequency is an important parameter, which can reflect the intensity of the vibration of the perforated plate. The higher the dominant frequency, the greater the strength of the vibration of the perforated plate, the stronger the interaction between the fluid. The amplitude curve of the pressure fluctuation can reflect the frequency characteristics of the typical flow in the flow field.

3. Results and analysis

3.1. Experimental setup

According to the amplification multiple information under different wind velocity, the acceleration signal is converted back into the original signal, and the vibration signal of different perforated plates in 0.01s under different wind velocity are intercepted. As shown in the figure 6, the acceleration signals of the perforated plate with a hole diameter of 3 mm in different wind velocity are drawn in the same image. It can be seen that the greater the wind velocity, the stronger the vibration amplitude of the acceleration signal. When the wind velocity is 10 m/s, the fluctuation of the acceleration signal is small. With the increase of wind velocity, the fluctuation of the signal is more obvious and the amplitude of the fluctuation is greater. The acceleration signals of different hole networks are basically consistent with the variation of wind velocity.
Due to the small displacement of perforated plates obtained by the acceleration signal, they are not convenient to observe. Therefore, the acceleration signal is represented by the RMS value. The displacement of perforated plates can be clearly observed from the RMS value. Figure 7 shows the RMS value of the acceleration signal under different parameters, and its basic parameters are shown in Table 3 and Table 4.

Table 3. RMS values for hole diameter and hole pitch.

| Velocity (m/s) | Hole diameter D (mm) | Hole pitch P (mm) |
|---------------|----------------------|------------------|
| 10            | 2.744x10^-4          | 6.266x10^-4      |
| 20            | 3.761x10^-4          | 3.761x10^-4      |
| 30            | 7.396x10^-4          | 3.831x10^-4      |

Table 4. RMS values for plate thickness and back space gap height.

| Velocity (m/s) | Plate thickness T (mm) | Back space gap height G (mm) |
|---------------|------------------------|-----------------------------|
| 10            | 6.676x10^-4            | 4.226x10^-4                |
| 20            | 2.554x10^-3            | 2.554x10^-3                |
| 30            | 5.677x10^-3            | 5.677x10^-3                |

Figure 7 (a) shows the RMS value of acceleration signals based on three different hole diameters at different wind velocities. It can be seen that when the hole diameter increased from 2 mm to 4 mm, the fluctuation of acceleration signal increased significantly, and the trend of variation became more irregular. Especially under large wind velocity, the displacement of the perforated plate changed more fiercely. In Figure 7 (b), the RMS value of acceleration signals with different hole pitch are shown. When the hole pitch is 4 mm, the interaction between the vertical flow and the surface of the perforated plate is stronger, and the vibration of the perforated plate is more obvious. As the hole pitch increases, the fluctuation of the acceleration signal decreases gradually, which indicates that the vibration amplitude of the perforated plate decreases. Figure 7 (c) is the effect of plate thickness on the random vibration of the perforated plate. It can be seen that when T=0.4 mm, the fluctuation of the acceleration signal is obvious. As the thickness of the plate increases, the fluctuation of the signal has a weakening trend. The results show that the smaller plate thickness will strengthen the random vibration trend on the perforated plate. Figure 7 (d) selected three back space gap heights to evaluate the impact of back space gap height on random vibration of the perforated plate. It is observed from the RMS value of the acceleration signal that the random vibration of the perforated plate is less affected with the change of the height of the gap.

Therefore, it can be concluded that the influence of wind velocity is obvious, with the increase of wind velocity, the vibration and deformation of the perforated plate gradually increase. The increase of hole diameter has the same influence on the random vibration of the perforated plate. On the other hand, with the increase of hole pitch and thickness, the deformation of perforated plates is weakened, which indicates that larger hole pitch and thickness are favorable for reducing random vibration of perforated plates. However, with the increase of the back space gap height, the deformation of the plate is very close. Only when the speed reaches 30 m/s, the height of back space gap has a certain effect on the random vibration of perforated plates. At this time, the deformation of perforated plates decreases first and then increases as the height of back space gap increases.
Figure 7. The influence of different parameters on RMS values. (a) Hole diameter D; (b) Hole pitch P; (c) Plate thickness T; and (d) Back space gap height G.

We can conclude that the random vibration of perforated plates at the middle position are the most serious, and the outer edge of perforated plates are secondary, as shown in Figure 8. Therefore, in order to ensure the safe operation of perforated plates, we must focus on the vibration of the middle part of the plate. Only by ensuring the stability of the middle part, can we ensure the safe operation of perforated plates.

Figure 8. Displacement distribution.

3.2. Spectrum analysis of pressure fluctuation

Figure 9 is a spectrum of fluctuating pressure of seven different measurement positions (M1-5, R, L, as shown in Figure 5) on the perforated plate (D=3 mm, P=5 mm, T=0.8 mm and G=10 mm) at different wind velocity. In Figure 9 (b), (d) and (f), it is obvious that the pressure fluctuation on the left and right sides of perforated plates are very close in the cross-stream position, and less than the center. As the wind velocity increases, the main vibrational position of perforated plates moves from the M1 point and the M3 point to the M5 point along the direction of the flow. It is indicated that with the increase of wind velocity, the amplitudes of pressure fluctuations gradually increase from the inlet to the outlet of main channel, and the fluctuating pressure near the outlet is significantly increased. It is clearly observed from the diagram that the frequency distribution of different monitoring points at the same wind velocity
is consistent. Figure 9 (a) and (b) represents the amplitudes of the wind velocity of 10 m/s. At this time, the fluid flow in perforated plates are relatively stable, and the dominant frequency is around 13.80 Hz, and the amplitude is maximum at the M1 point, and the M3 point is the second. This means that in the wind speed of 10 m/s, the vibration of perforated plates is mainly concentrated at the M1 point and the M3 point of the plate. With the further improvement of the wind velocity, the fluid flow in the backspace of perforated plates becomes irregular. As shown in figure 9 (c) and (d), there are no obvious peak in the region of 0-20 Hz, but a wide frequency distribution. The emergence of broadband may be attributed to the coupling of complex fluid and perforated plates near the probe region. Three peaks can be observed after the broadband, one at 19.5 Hz, the second in 25.7 Hz, and the last in 34.8 Hz. At this time, the vibration amplitude of each position of the perforated plate is relatively close, and there is no prominent position of vibration. However, the amplitude increases relative to the small wind velocity. When the wind velocity increases to 30 m/s, the fluid flow in the perforated plate is quite turbulent. As shown in figure 9 (e) and (f), there are two peaks in the graph, one is in 13 Hz, the other is in 39 Hz, and the amplitude of one frequency doubling is obviously higher than that of three frequency doubling. At the same time, the main vibration position of the perforated plate is transferred to the M5 point under the wind velocity of 30 m/s. At this time, the vibration of perforated plates is very serious, and the wind velocity has great influence on the stability of perforated plates, which is extremely unfavorable to the application of perforated plates.

![Figure 9](image_url)

**Figure 9.** Effect of wind velocity on the PSD. (a) Stream direction of 10 m/s; (b) Cross-stream direction of 10 m/s; (c) Stream direction of 20 m/s; (d) Cross-stream direction of 20 m/s; (e) Stream direction of 30 m/s; and (f) Cross-stream direction of 30 m/s.
In order to facilitate analysis, the dominant frequency and its corresponding amplitude are listed in Table 5. From table 5, we can see the effect of different parameters on the amplitude of the pressure fluctuation of perforated plates. Under the same wind velocity, the dominant frequency is not affected by the changes of the parameters. Therefore, we believe that the random vibration characteristics of perforated plates are independent of the dominant frequency. To study the random vibration characteristics of the perforated plate, we need to pay attention to the amplitude variation caused by the variation of each parameter. As shown in table 5, the vibration amplitude of the M3 point increases with the increase of hole diameter at the wind velocity of 10 m/s. It is indicated that the hole diameter has obvious influence on the random vibration of the perforated plate. As the hole diameter becomes larger, the fluid flowing into or out of the cavity below perforated plates becomes easier. In this way, the mixing of fluid in the cavity is serious, which makes the large scale vortex in the cavity of perforated plates have a tendency to transform to the small scale. The decrease of the vortex scale makes the internal flow of the cavity flow more turbulent, which further aggravates the vibration of perforated plates. The amplitude of the M3 point decreases gradually when the hole diameter remains constant and the size of the hole pitch increases. This is due to the increase of the hole pitch, which leads to the decrease of the number of holes. In other words, when the hole diameter is consistent, the amplitude of perforated plates decreases with the decrease of the number of holes. When the thickness of perforated plates increases, the structure of the plate becomes more stable, and the effect of fluid disturbance on the vibration of the plate is more difficult. As shown in table 5, with the increase of plate thickness, the amplitude of the M3 point is obviously reduced, indicating that the thickness of the plate has a great effect on the vibration of perforated plates. With the increase of back space gap height, the amplitude variation of the M3 point of the perforated plate is nonlinear. As the height increases, the amplitude of the M3 point decreases first and then increases gradually.

Table 5. Spectrum analysis of pressure fluctuations for different parameters under 10m/s wind velocity.

| Parameters | Dominant Frequency $f_d$/Hz | Amplitude at $f_d$/Pa |
|------------|-----------------------------|-----------------------|
| D2         | 13.70                       | 0.2069                |
| D3         | 13.80                       | 0.2489                |
| D4         | 13.85                       | 0.2857                |
| P4         | 13.75                       | 0.2676                |
| P5         | 13.80                       | 0.2489                |
| P6         | 13.66                       | 0.2456                |
| T0.4       | 13.95                       | 0.3399                |
| T0.8       | 13.80                       | 0.2489                |
| T1.2       | 13.80                       | 0.1502                |
| G3         | 13.53                       | 0.7058                |
| G6         | 13.80                       | 0.2489                |
| G10        | 13.85                       | 0.7450                |

4. Conclusions
In this study, according to the displacement deformation measured by the acceleration signal sensor and the fluctuating pressure obtained by the pressure difference sensor, the conclusion of the random vibration analysis of the perforated plate is basically consistent. The results show that the wind velocity, hole diameter, hole pitch, plate thickness and back space gap height are the key factors that affect the random vibration of the perforated plate. The main manifestations are as follows:

- With the increase of the wind velocity and the hole diameter, the random vibration of the perforated plate is enhanced.
- With the increase of hole pitch and plate thickness, the amplitude of the perforated plate decreases gradually.
- With the increase of back space gap height, the amplitude of the perforated plate has a tendency to decrease first and then gradually increase.
In the stream direction of the perforated plate, the vibration of the plate is mainly concentrated in the middle and tail of the plate, so the fluid force in the center of the plate is larger, and the fluid in the trailing edge of the perforated plate is more chaotic.

In conclusion, lower wind velocity, smaller hole diameter, larger hole pitch, larger plate thickness and appropriate back space gap height play a positive role in reducing the fluid exciting force of perforated plates. Therefore, optimizing the parameters, including the hole diameter and hole spacing and so on, can generate a promising effect on reducing vibration of the perforated plate.

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