Passive Perforated Pipe Control Method for Wind-Induced Vibration of a High-Rise Chemical Tower

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Abstract: Vortex-induced vibration is likely to occur when subjected to wind loads because of low horizontal stiffness, resulting in internal force and large lateral amplitude. Long-term wind-induced vibration can not only affect the normal service and durability performance of chemical towers, but also seriously endanger the safety of towers in service periods, and cause property losses. In this study, a passive control method for suppressing wind-induced vibration of chemical towers is proposed. The flow around the flow field is guided by a pre-set air-blowing channel, thus destroying the unsteady vortex shedding in the wake region of the flow field and achieving the purpose of flow control. Two accelerometers are used to measure the vibration signal of the chemical tower model with and without the perforated pipe. The control effects of the spacing and the installation position of the perforated pipe are then studied. Experimental results show that the passive perforated pipe control method can effectively reduce the vibration amplitude of the chemical tower under wind loads, and decrease the potential wind-induced vibration.

Key words: chemical tower; wind-induced vibration; pneumatic control

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0 Introduction

As industrial technology develops, more and more high-rise buildings and even super high-rise buildings emerge rapidly. High-rise structures are widely used in electric-power, communications, chemical and other industries. In most cases, wind load is the control load of a high-rise structure as a slender structure with high height and low stiffness. Since higher demands have been raised for production, high-rise structures become more flexible and sensitive to wind loads.

For high-rise structures like transmission tower, the wake vortex shedding is insignificant, and the cross-wind vibration is not obvious. However, the enclosed high-rise structure in petrochemical industry, like ethylene distillation tower, is flexible. The horizontal lateral stiffness is relatively low because of its great height (generally about tens of meters) and empty interior, and the first vibration frequency is generally less than 1.0 Hz. Therefore, vortex-induced vibration is likely to occur. The long-term wind-induced vibration can also affect the performance, production and operation of chemical towers in service periods. To this end, this study proposes a passive air-blowing perforated pipe flow control method to reduce the wind load and wind-induced vibration response of circular high-rise chemical tower, thus ensuring the wind-resistant safety of chemical towers.

Vortex-induced vibration of a chemical tower under wind loads is a common phenomenon in its service period. The model of a chemical tower after

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scale transformation can be approximated as a slender cylinder, which is a classical problem of flow around a cylinder. In 1911, the famous Karmen Vortex Street was discovered. In the wake region of the cylinder, the vortices can be observed to shed alternately with frequency f_s. The periodic shedding of the vortices causes periodic variation of the pressure difference near the surface of the structure, which is equivalent to a periodic force, namely vortex-induced force. If the shedding frequency of the vortices is close to the natural frequency of the structure, resonance will occur.

In engineering practice, adding dampers is the most direct way to achieve vibration control. Dampers include rubber dampers, viscous dampers, magnetorheological dampers, and so on. Modi et al.[1] added suspended obstacles to sloshing liquid dampers (SLD) to increase the energy efficiency of dampers, finding the energy dissipation efficiency of dampers could be significantly improved by the wedge-shape suspended material. The damping coefficient can be increased by 86% by changing the surface roughness of the wedge shape. Mendonca et al. [2] proposed a hybrid mass damper (HMD) based on fuzzy logic control. The automatic orientation function set on HMD can distinguish the lateral displacement of the structure, so that the displacement in any horizontal directions can be controlled. Tani et al.[3] used viscoelastic rubber dampers with high hardness and stiffness to improve the comfort and safety of high-rise buildings under wind loads. The natural frequencies of the dumpers were less affected by temperature. Wind tunnel tests show that the dampers can significantly reduce the wind-induced vibration of high-rise buildings, and especially have obvious control effects on the structural vibration acceleration.

In addition, the aerodynamic control method has been widely used, which can be divided into active control and passive control according to the need for external energy input. Passive control is mainly achieved by modifying the geometry of the cross section, while active control is realized by injecting additional energy.

A lot of active flow control methods have been suggested to control the vortex shedding in the wakes behind bluff bodies to suppress VIVs. Cheng and Shao[4] studied the vortex shedding through the control method of tail jet in cylindrical flow by using computational fluid dynamics (CFD) technology. The simulation results show that the jet wake can suppress the vortex shedding when the jet speed is in a suitable range. Feng et al.[5-7] conducted a series of experimental studies, finding that synthetic jets at the rear stagnation points of circular cylinders could be used to impose symmetric perturbations on the cylinder flows and modify the vortex shedding mode. Xu et al.[8] used a numerical simulation method to discuss the effect of a traveling wave wall on the control of vortex-induced vibration, and found that the traveling wave wall could restrain the boundary layer separation on the surface of cylinder, thus reducing the shedding of vortices and restraining the generation of vortex-induced vibration. Xu et al.[9] successfully realized the suppression effect of traveling wave wall test on vortex-induced vibration in the condition of wind tunnel, which provided practical experiment support for theoretical studies.

Several passive flow control methods have been suggested to manipulate the vortex shedding process in the wakes behind the bluff bodies. Kwok and Bailey[10] proposed a passive aerodynamic control method to suppress the wind-induced vibration of square buildings. Wind tunnel tests verify that the aerodynamic method can alleviate the wind-induced vibration response of structures. Zhou et al.[11] experimentally investigated the flow passing a circular cylinder with dimpled surface in the Reynolds number range of 7.43×10^3 to 1.798×10^4. The study revealed that the cylinder covered with uniform dimples could reduce the drag coefficient 10% in comparison with a smooth cylinder. Dutton and Isyumov[12] proposed to reduce the wind-induced vibration response of the structure by seaming the upper half of a building, and carried out relevant wind tunnel experiments. Wu et al.[13] numerically investigated vortex-induced vibration of an elastically mounted circular cylinder with a hinged flat plate, finding the cylinder vibration and the force fluctuations could be efficiently suppressed by the hinged plate. Shi and Feng[14] investigated the bleed control of a circular cylinder by forming narrow slots from the windward stagnation point to both the upper and the lower separation points. The flow measurement results demonstrate that the bleed jet postponed the separation point to the downstream edge of the slot, thus increasing the vortex formation length and decreasing the vortex shedding frequency. As stated by Gao et al.[15] the slit generated a self-issuing jet into the cylinder wake and the passive jet effectively manipulated the wake vortex shedding process from the circular cylinder. A linear stability analysis suggests that the intrinsic nature of the cylinder wake flow is greatly modified with the implementation of a slit.

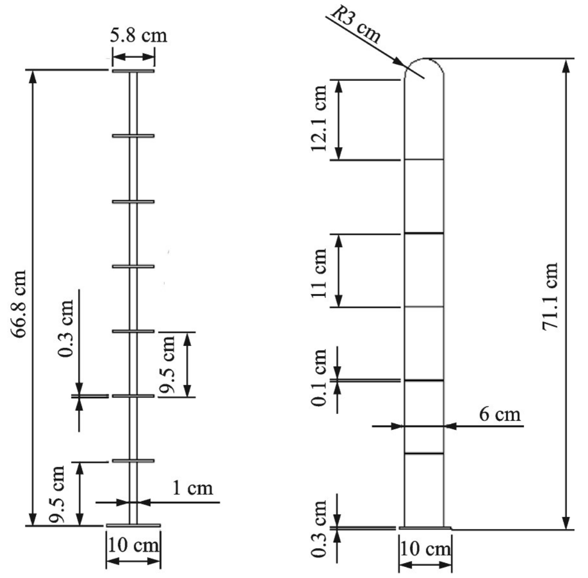
In summary, the high-rise chemical tower, as a typical flexible slender structure, has high sensitivity to wind. In this study, a new passive control method of vortex-induced vibration (VIV) which installs some perforated pipes around the chemical tower is proposed. By evaluating the effect of reducing the vortex-induced vibration, an effective method of suppressing the vortex-induced vibration is explored. By evaluating the feasibility of the proposed method in practice, it can be further applied in production.

1 Test Model and Experimental Setup

The experimental measurements are conducted in a wind tunnel affiliated with the joint laboratory of wind tunnel and wave flume (J. Lab. WTWF), Harbin Institute of Technology, P. R. China. The closed-circuit wind tunnel has a test section of 800 mm (width) ×1 200 mm (height), and the walls are made of transparent materials. A contraction section with honeycombs and mesh structures is installed upstream of the test sections to generate uniform incoming airflow into the test sections. The flow field in the test sections is stable, and the turbulence intensity level of these sections is relatively low (0.4%) based on the measurement with a hot wire anemometer.

1.1 Test model

Considering the original structure of the chemical tower in the engineering background, a scale model of the aeroelastic chemical tower is made according to a certain scale ratio while ignoring some details. The scale ratio of the model is 1∶100, the height of the model is $H=71.1$ cm and the diameter of the tower body is $D=6$ cm. The components with little influence on the aerodynamic characteristics of the chemical tower, such as holes, ballast isolators and hangers are not considered. The framework is made of hollow aluminium alloy, and the coat is made of 3-D resin printing material. The tower body, head and pedestal are tightly bonded with glue. The model skeleton and coat dimensions are shown in Fig.1.



(a) Model skeleton dimensions (b) Coat dimensions

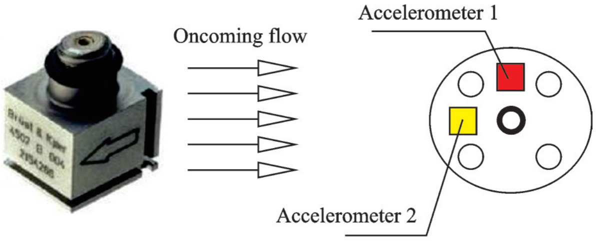
Fig.1 Model skeleton and coat dimensions

The aeroelastic model is complex and requires high precision. In the aeroelastic chemical tower model, an aluminum alloy straight rod with a diameter of 1 cm is used to simulate the original structural stiffness. The similar mass ratio of the original structure is simulated by using an aluminum alloy platform with a diameter of 5.8 cm and a thickness of 0.3 cm welded on the aluminum alloy straight rod. A total of seven counterweights are set and the net distance of each counterweigh is 9.5 cm. The thin aluminum alloy plate base with a diameter of 10 cm and a thickness of 0.5 cm is circumferentially welded at the bottom of the framework. The total height of the framework and the base is 66.8 cm. A 3-D printing coat simulates the shape of the original tower structure, which consists of five coats with 7 cm height and 6 cm diameter. The top of the tower is printed according to the original structure shape. Based on the finite element software ABAQUS, the natural frequency of the model is 7.05 Hz and the damping ratio is 0.188. The model is shown in Fig.2.

(a) Model skeleton (b) Original model (c) Experiment model

Fig.2 Model and perforated pipe layout of scaled aeroelastic chemical tower

Vortex-induced vibration of chemical tower is caused by unsteady vortex shedding of wake. A group of perforated pipes are arranged on the chemical tower at a specified distance, and some holes are set on the surface of the perforated pipes. The oncoming flow enters the air holes near the front stagnation point, passes through the pre-set channel in the perforated pipes, and finally blows out from the air holes near the back-stagnation point. The airflow destroys the unsteady shedding around the wake area of the flow field and realizes the flow control. Since the method does not require additional energy, it is applicable to engineering practice. In this experiment, the control effect of changing the spacing along the perforated pipe and the position of the perforated pipe is studied. The design and installation of the sleeve in this experiment are shown in Fig.2.



(a) Accelerometer (b) Instrument layout

Fig.3 Experiment arrangement

1.2 Experimental setup

In this experiment, an accelerometer system is used to collect the acceleration signal of wind-induced vibration of structures, as shown in Fig. 3. The principle of accelerometer is as follows. In wind tunnel test, the accelerometer is fixed on the vibration model, and the arrow of the accelerometer points to the measurement direction of structural vibration. The model vibration drives the vibration of the accelerometer connected with the accelerometer sensor calibration system. The accelerometer calibration system transfers the acceleration signal to the system. The electronic signals are converted and collected by LabVIEW programming system, and the acceleration signal data are converted into displacement signal data by MATLAB programming system.

In the experiment, special attention should be paid to the measurement direction of acceleration and the method of fixing the accelerometer. The arrow direction on the side of the accelerometer is the displacement direction of the measurement structure. No relative displacement exists between the accelerometer and the structure. Improper operation can lead to the error.

The basic natural frequency of the aeroelastic model used in the experiment is 7.05 Hz. According to the calculation formula of Strouhal number, the critical wind speed is about 2.115 m/s, and the lock-in wind velocity regions is about 2.115 m/s to 2.75 m/s. Therefore the model is tested under the frequency of the fan from 5 Hz to 14 Hz, and the corresponding wind speed is 1.55 m/s to 6.33 m/s. The accelerometers are arranged at the top of the model skeleton. The acceleration signals are collected in the directions of X and Y, i.e. the axial and cross directions of oncoming flow. The frequency adjustment range of the fan is from 5 Hz to 14 Hz, and the sampling time is 30 s. Four groups of acceleration signal data are collected for each fan frequency, and Group 2 and Group 3 are taken as the test analysis data. The acceleration of the model under vortex-induced vibration is obtained.

Acceleration signals are collected by the accelerometer system, and saved as LVM file by the accelerometer acquisition system. The signal is converted into displacement signal through MATLAB program for further analysis.

2 Measured Results and Discussion

2.1 Influence of the spacing of the perforated pipe on the control effect

In this section, the spacing of the perforated pipe S on the model of chemical tower is changed and the acceleration signals of the model under different wind speeds are measured by accelerometers, which are analyzed by the above-mentioned methods. Seven cases are set in the experiment as follows: uncontrolled, $S=1D$, $S=2D$, $S=3D$, $S=4D$, $S=5D$ and $S=6D$. The height of the perforated pipe is 30 mm, and the inner diameter is 62 mm. A total of 24 holes are evenly distributed. The cavity height is 15 mm, and the thickness is 5 mm. The arrangement of the perforated pipe is shown in Fig.4.

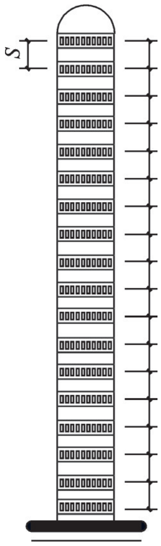


Fig.4 Layout of the perforated pipe under different perforated pipe spacing

Fig. 5 shows the curve of RMS of cross-wind displacement responses of the chemical tower model varying with wind speed under different perforated pipe spacing S.

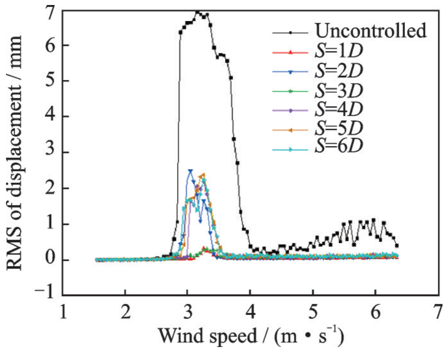
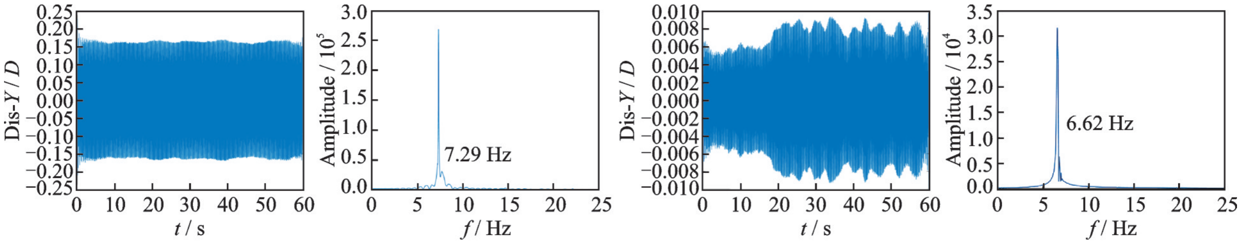


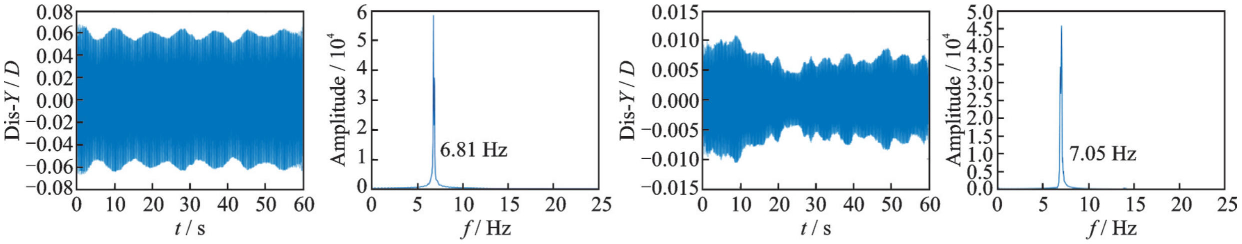
Fig.5 RMS of cross-wind displacement responses varying with wind speed under different perforated pipe spacing

From Fig.5, it can be observed that the maximum RMS of displacement decreases obviously after the model surface is covered with the perforated pipe. The significant reduction of the maximum RMS of displacement shows that the passive perforated pipe control method can effectively control the vortex-induced vibration of chemical towers. By comparing the maximum RMS of displacement under different perforated pipe spacing, the maximum RMS of displacement in all cases is reduced to less than 35.7% compared with that in the uncontrolled case. When $S/D=3$, the value is reduced to about 7%. Therefore, the control effect of $S/D=3$ is the most obvious. Obviously, when $S/D=6$, the control effect is not as good as that in other cases. The possible reason is that when the spacing between the perforated pipes is too large, the flow field between the perforated pipes is not disturbed well by perforated pipes, thus weakening the control effect.

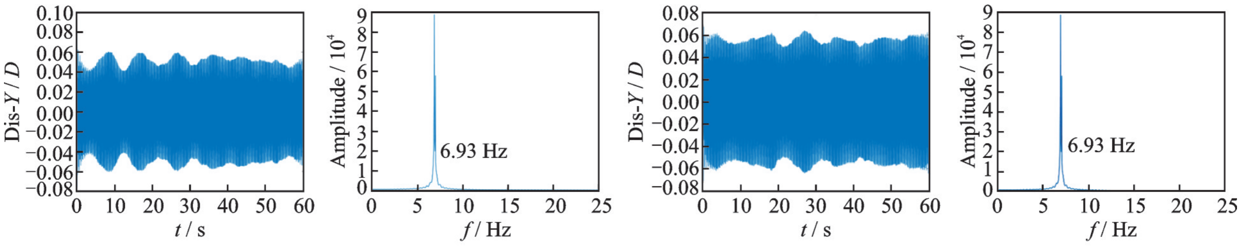
The time-histories of cross-flow vibrations in different cases are shown in Fig. 6. For sesults in



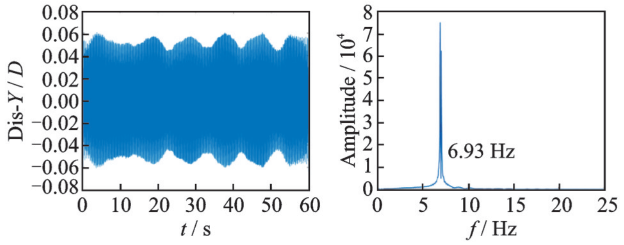
(a) Uncontrolled (b) S=1D



(c) S=2D (d) S=3D



(e) S=4D (f) S=5D



(g) S=6D

Fig.6 Time histories and frequency spectra of the cross-flow vibrations of the test model in different cases

each case, the left figure is the displacement response (the ordinate is the ratio of displacement to model diameter) and the right one is the corresponding sepctrogram. It can be seen from Fig.6 that the corresponding displacement in each case decreases compared with that in the uncontrolled case. When the spacing of the perforated pipes is 1D, 2D, 3D, 4D, 5D and 6D, the dimensionless values of maximum displacement are 0.06, 0.33, 0.05, 0.33, 0.33 and 0.33 times of the dimensionless values under the uncontrolled case, respectively. When $S/D=3$, the cross-wind vibration displacement decreases the most substantially and the control effect is the best, which is consistent with the above conclusions. From the displacement response time-history diagram, it can be found that the perforated pipe control method has a great control effect on the wind-induced vibration of the chemical tower. Choosing appropriate perforated pipe spacing can achieve a good control effect.

2.2 Influence of the installation position of the perforated pipe on the control effect

In this section, the installation position of the perforated pipe is changed, and three perforated pipes are arranged at different positions of the chemical tower model. The acceleration response of the model under different wind speeds is also measured by accelerometers. When three perforated pipes are arranged, the spacing of perforated pipes is $S/D=1$. As the distance between upper perforated pipe and the top of the tower is Z, four cases are set in the experiment as follows: uncontrolled, Z=6 cm, Z=21 cm and Z=36 cm. Fig.7 describes the layout of the perforated pipes when Z=6 cm, and the layout is similar in other cases.

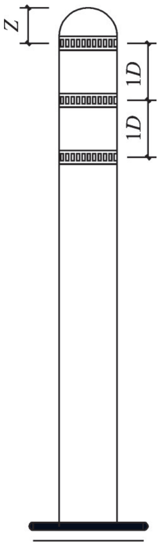


Fig.7 Layout of perforated pipes under different installation positions

Fig. 8 shows the curve of RMS of cross-wind displacement responses of the chemical tower model varying with wind speed under different Z. It can be seen that the maximum RMS of displacement in each case is obviously reduced compared with that under uncontrolled case, except for Z=36 cm. Comparing the maximum RMS of displacement under different distances between upper perforated pipe and the top of the tower, the value is reduced to 42.9% under uncontrolled case when Z=6 cm. When Z=21 cm and Z=36 cm, the values are 57.1% and 171%, respectively. We can observe that the control effect is the best when Z=6 cm, and the control effect decreases with the increase of Z. When Z=36 cm, the existence of the perforated pipe does not work, but enhances the cross-wind vortex-induced vibration. The damage of high-rise chemical towers is generally caused by vortex-induced vibration, so it is reasonable to install the perforated pipe near the top of the tower.

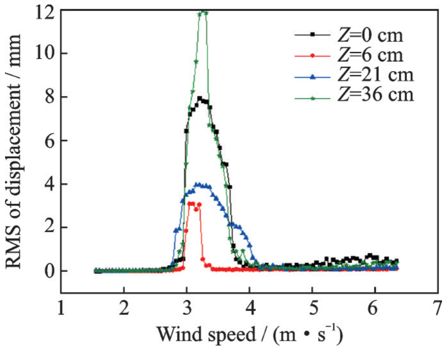
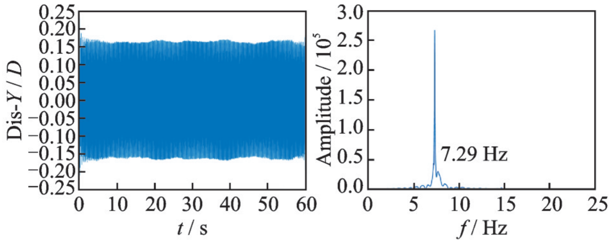
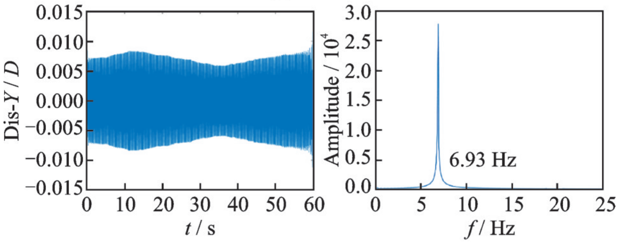


Fig.8 RMS of cross-wind displacement response varying with wind speed

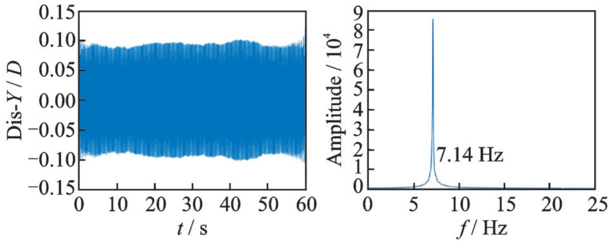
Fig. 9 shows the time-history of cross-flow vibrations in different cases. The left figures are the displacement response (the ordinate is the ratio of displacement to model diameter), and the right figures are the corresponding spectrogram. When Z = 6, 21 and 36 cm, the dimensionless values of the maximum displacement are 0.4, 0.6 and 1.7 times



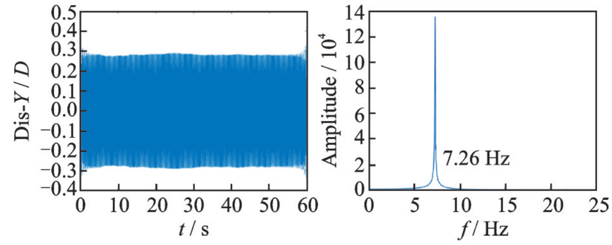
(a) Uncontrolled



(b) Z=6 cm



(c) Z=21 cm



(d) Z=36 cm

Fig.9 Time histories and frequency spectra of the cross-flow vibrations of the test model of that in the uncontrolled case, respectively. When $Z=6$ cm, the vibration displacement in the cross-wind direction decreases the most substantially, and the control effect is the best. When $Z=36$ cm, the vibration displacement in the cross-wind direction increases compared with the uncontrolled case, and the control effect is not achieved, which is consistent with the above conclusions.

3 Conclusions

This study proposes an aerodynamic control method for suppressing vortex-induced vibration of chemical towers by installing perforated pipes.

Tunnel test results show that the wind load on the surface of the chemical tower can be greatly reduced by installing perforated pipes under a reasonable layout. The spacing and location of the perforated pipes can significantly influence the aerodynamic characteristics of the chemical tower. The control effect is the most obvious when the spacing between perforated pipes is $S=3D$. When the spacing between the perforated pipes is too large, the control effect of the perforated pipes is inferior to that in other cases. The possible reason is that the flow field between the perforated pipes cannot be disturbed well under large spacing, thus weakening the control effect. Therefore, the spacing between the perforated pipes should be reasonably selected.

The installation position of the perforated pipe also has great influence on the aerodynamic characteristics of the chemical tower. When the perforated pipe is closer to the top of the model, better control effect can be achieved. On the contrary, when the perforated pipe is closer to the middle of the span, the control effect is worse, and the displacement response of the vortex-induced vibration can be enhanced. Therefore, it is reasonable to install the perforated pipe close to the top of the tower.

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Author contributions Prof. **CHEN Wenli** and Dr. **LU Shanshan** are the project directors. Mr. **ZHANG Runtao** designed the details of the experiment. Mr. **ZHANG Zhifu** wrote the manuscript. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: WANG Jing)

高耸化工塔风致振动的被动套环控制

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摘要:化工塔结构水平方向刚度较小,受风荷载作用时,易产生涡激振动现象,进而产生较大横向振幅和内力。长期风致振动会影响化工塔的正常使用和耐久性能,严重危害其服役期内的安全。本文提出利用套环抑制化工塔风致振动的被动控制方法,预设吹气通道来引导绕流场的流动,从而破坏绕流场尾迹区的非定常旋涡脱落,达到流动控制的目的。本文通过加速度传感器测量化工塔模型在安装套环前后的加速度信号,再利用编程软件将其转换为位移信号数据,研究分别改变沿塔身套环布置的间距以及套环布置的位置的控制效果。试验结果表明,被动吸气套环控制方法能有效减小化工塔在风荷载下的振动幅度,从而能减小潜在风致振动。

关键词:化工塔;风致振动;气动控制