Experimental study on vibration of air cooling fan bridges

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Abstract. ACC (air cooled condenser) is widely used in coal-fired power plants. It has the advantages of water saving and energy saving, and the system is simple. The fan bridge is an important part of the ACC. At present, the vibration problem of the fan bridge is very much, and the experimental data of the bridge vibration is single, and the fundamental vibration source problem is not revealed. Therefore, it is important to study the vibration causes of the wind turbine bridge. This paper analyzes the possible causes of vibration of the fan bridge. Through the combination of field test and theoretical analysis, the main causes of bridge vibration are analyzed. Research shows that air disturbance is the main cause of bridge vibration. The research results provide basis for bridge design.

1. Introduction

Water cooling technology of thermal power plants needs to consume a large amount of water resources, which leads to great restrictions about selecting place of power plant. In recent years, since the shortage of water resources, water cooling technology has gradually been replaced by air cooling technology. The technology uses forced convection of fans to cool the exhaust steam in the tube bundle. A general 600MW unit requires 56 fan units, with a single fan diameter of about 10 meters. The fan is installed on the fan bridges. During the operation of the fan, the fan bridges will vibrate. Excessive vibration will cause damage to fans, motors, speed reducers, etc. In 2008, the vibration of the fan bridges in the air-cooling island of Huai’ an Power Plant was too large, which resulted in the vibration of the fan bridges exceeding the standard. In the later period, the fan bridges had to be strengthened, with a total renovation cost of several million yuan. Therefore, it is necessary to explore the causes of the vibration of the fan bridges and provide basis for the design of the fan bridges in the later period [1].

There are many researches on the vibration of fan bridges. Dou Ruijie [2, 3, 4] carried out a series of dynamic strain tests and analyses on a 1:1 bridge model. It is concluded that the three disturbing forces causing the bridges vibration are the eccentricity of the fan rotor, the out-of-plane vibration of the fan blades and the torque. Zhao Fei et al [5] tested different combinations of four fans respectively, studied the influence of multiple fans on the vibration response of the bridges, analyzed the maximum displacement of the vibration response of the bridges center and the influence of phase difference on the vibration response of the bridges. The experimental data of this study show that the vibration of each typhoon affects each other. Xiong Yinseng [6] measured the vibration of the bridges on the spot, and
listed the vibration situation and frequency spectrum of each point in the data analysis. Liu ling and others carried out experimental tests and analyses on the vibration of the fan bridges. The research shows that in the bridges design process, the natural vibration frequency of the bridges should be avoided from the frequency generated by the fan under the working condition to avoid resonance.

This paper analyzes the possible causes and vibration characteristics of several air-cooled fan bridges, and explores the main frequencies that affect the vibration of fan bridges and the main causes of the frequencies through tests. The first part of this paper introduces the fan bridges and vibration test, the second part explores the causes and vibration characteristics of the bridges vibration, the third part carries out hammering experiments on the bridges, and the fourth part puts forward the main causes of the bridges vibration and the solutions to avoid the bridges vibration. The fifth part summarizes this article.

2. Fan bridges and vibration test

2.1. Overview of fan bridges
The height of the air-cooled platform where the fan bridges is located is 22 meters. There are six cooling units, which are composed of fans, bridges and fins, arranged in two rows side by side. Each cooling unit contains a fan and a bridge supporting the fan, as shown in fig.1. The span of the bridges is 9.1 meters, and the main body consists of H-shaped steel. The fan is driven by motor and decelerated by reduction gearbox. Fans, reducers and motors are installed in the middle of the bridges. The installation of speed reducers and motors is shown in fig.2. The speed reducer is of secondary speed reduction and is installed in a parallel vertical shaft type. The rotating speed of the motor is controlled by the frequency converter, and the rotating speed control range is 30% - 110%.
Table 1. Parameters of Fans

| Parameter                        | Value       |
|----------------------------------|-------------|
| Total mass of fans               | 449 kg      |
| Number of blades                 | 6           |
| Reduction ratio                  | 9.308       |
| Rated speed of motors            | 1480 min⁻¹  |
| Speed control range              | 50% - 110%  |

2.2. Test plans
In order to solve the vibration problem of the bridge. Firstly, the forced vibration experiment of the bridge is carried out. The bridge is excited by different rotating speeds of the fan, and the vibration condition of the bridge is tested, so that the frequency components causing the bridge to vibrate greatly are extracted. Secondly, the inherent frequency of the bridges itself is the key frequency for the bridge to generate resonance. In order to avoid resonance, hammering experiments are needed to obtain the inherent frequency.

2.3. Testing Instruments and distribution of sensors
The testing instruments mainly include LMS data acquisition instrument and acceleration sensor of B&K Company. According to the above test scheme, in the natural vibration characteristic experiment, the sensors are uniformly arranged on the bridge. The sensor arrangement diagram is shown in fig.3. In the forced vibration experiment, because the vibration of the main girders on both sides of the bridge is similar, the arrangement position of the sensors is simplified. The sensor arrangement diagram is shown in fig.4.
3. Vibration tests of fan bridges

3.1. Forced vibration tests

According to the working requirements of fans, there are 4 working conditions from low speed to high speed. Since it is the same as the peak points corresponding to sensors 1, 3, 12 and 17, furthermore, the vibration of sensors 1 and 3 is relatively large. Therefore, the frequency domain part with larger vibration under various working conditions of sensor 1 is selected, as shown in fig. 5. The main frequency range causing bridge vibration is from 5Hz to 14Hz. By analyzing the data of various working conditions, we found that there are 4 parts’ frequency causing the vibration of bridge: (1) the frequency is equal to the product of the fan shaft frequency and the number of blade, which is called blade frequency. According to the results of research [7], it is known that the frequency of the blade is the same as or similar to the frequency of vortex excitation under various working conditions. Through experiments, it is verified that the blade frequency interference is caused by vortex excitiation force, and causing the unstable operation of the fan. Blade frequency interference has been studying in relevant papers. (2) 5 times of the fan shaft frequency; (3) 4 times of the fan shaft frequency; (4) 3 times of the fan shaft frequency.

![Figure 3. Distribution of Sensors](image1)

![Figure 4. Distribution of Sensors](image2)

![Figure 5. No.1 Sensor frequency domain diagram](image3)
Blade frequency is also called passing frequency. Simple to say, each fan has 6 blades passing through every rotation, which is same wherever you see. During its operation of the fan, a continuous integer frequency multiplication is generated when the fan blades are completely asymmetric. Its theoretical analysis is basically consistent with the experimental results. However, the blades are completely symmetrically arranged after debugging in the installation process of the fan, and integer frequency multiplication will not occur theoretically. Therefore, fan’s range of rotating speed is expanded, and the fan is frequency-modulated from 20Hz to 50Hz. The results are shown in Table 2, the theoretical frequency of the fan is compared with the experimental analysis results.

| No | mains frequency (Hz) | the fan shaft frequency (Hz) | blade frequency (Hz) | Test blade frequency (Hz) | 5xthe fan shaft frequency (Hz) | Test 5xthe fan shaft frequency (Hz) | 4xthe fan shaft frequency (Hz) | Test 4xthe fan shaft frequency (Hz) | 3xthe fan shaft frequency (Hz) | Test 3xthe fan shaft frequency (Hz) |
|----|----------------------|------------------------------|----------------------|--------------------------|-------------------------------|----------------------------------|-------------------------------|----------------------------------|-------------------------------|----------------------------------|
| 1  | 25                   | 1.089                        | 6.536                | 6.475                    | 5.446                         | --                               | 4.357                         | --                               | 3.268                         | --                               |
| 2  | 27.5                 | 1.198                        | 7.189                | 7.1                       | 5.991                         | --                               | 4.793                         | --                               | 3.595                         | --                               |
| 3  | 30                   | 1.307                        | 7.843                | 7.775                    | 6.536                         | --                               | 5.229                         | --                               | 3.921                         | --                               |
| 4  | 32.5                 | 1.416                        | 8.496                | 8.425                    | 7.080                         | --                               | 5.664                         | --                               | 4.248                         | --                               |
| 5  | 35                   | 1.525                        | 9.150                | 9.075                    | 7.625                         | --                               | 6.100                         | --                               | 4.575                         | --                               |
| 6  | 37.5                 | 1.634                        | 9.803                | 9.75                     | 8.170                         | --                               | 6.536                         | --                               | 4.902                         | --                               |
| 7  | 40                   | 1.743                        | 10.457               | 10.4                     | 8.714                         | --                               | 6.971                         | --                               | 5.229                         | --                               |
| 8  | 42.5                 | 1.852                        | 11.111               | 11.05                    | 9.259                         | 9.2                              | 7.407                         | 7.375                            | 5.555                         | 5.525                            |
| 9  | 45                   | 1.961                        | 11.764               | 11.7                     | 9.803                         | 9.75                             | 7.843                         | 7.8                              | 5.882                         | 5.85                             |
| 10 | 47.5                 | 2.070                        | 12.418               | 12.35                    | 10.348                        | 10.3                             | 8.278                         | 8.25                             | 6.209                         | 6.175                            |
| 11 | 50                   | 2.179                        | 13.071               | 13                       | 10.893                        | 10.85                            | 8.714                         | 8.675                            | 6.536                         | 6.5                              |

According to the above research, we found that blade frequency always exists in the process of the fan from low speed to high speed, which is consistent with the research above. The third, fourth and fifth frequency multiplication of the fan occurs at high rotating speed, but there is no second frequency multiplication in the integer frequency multiplication of the fan.

After the installation of the fan, the fan blades are completely symmetrically arranged, integral frequency multiplication will not occur during operating. The integer frequency multiplication in the experiment shows that the fan blades are deformed. It is air resistance that causes the deformation of fan blades. The higher the fan’s rotating speed, the greater the air resistance the fan blades are subjected to, and air resistance causes the vibration of fan blades. The blades’ vibration causes its completely asymmetric state, resulting in integer frequency multiplication.

According to the theory above, the air resistance of the fan in the process of low rotation speed is relatively small, which does not cause obvious vibration of the blades, so integral frequency multiplication will not occur. But the air resistance will jump with the increase of the rotation speed of the fan. After reaching a certain rotational speed, the blade will deform. As shown in Table 2, there is no integer frequency multiplication when the fan is running under low operating conditions. After
42.5HZ operating conditions, integer frequency multiplication appears. The theoretical analysis above is completely consistent with the experimental data analysis results, which shows that the blades are vibrated under the action of air resistance during the high-speed operation of the fan, thus generating integer frequency multiplication.

In the integer frequency multiplication, the second frequency multiplication does not appear or there is no obvious peak point, which may be due to the large difference between the natural frequency of the bridge and the second frequency multiplication frequency, and there is no obvious peak point. Therefore, it is necessary to carry out hammering experiments on the bridge. If the natural frequency of the bridge is within the frequency range of the third, fourth and fifth frequency multiplication of the fan and blade frequency, and second frequency multiplication is far away from the natural frequency, then the assumption above is proved to be correct.

3.2. Modal test

According to the test results of forced vibration, it can be seen that the blade frequency and the third, fourth and fifth frequency multiplication of the fan are the main frequencies that cause the vibration of the bridge, while the other frequencies generated by the fan have less influence on . It may be due to the natural frequency of the bridge being located in this region. Therefore, a hammering experiment is carried out on the bridge to calculate the bridge natural frequency. As shown in fig.6, it is the frequency domain diagram of the bridge hammering experiment.

![Figure 6. Frequency domain diagram of bridge](image)

The five natural frequencies of the bridge assembly are extracted, as shown in Table 2. The first five-order frequency range of the bridge is 6.668HZ-12.005HZ. the blade frequency, the third, fourth and fifth frequency multiplication of the fan are place to the range. As shown in Table 3, it is the double frequency of the bridge. Comparing Table 2 with Table 3, it is found that the double frequency generated by the fan are not place in the resonance region of the bridge, so there is not obvious peak point, so the theoretical analysis is correct.

| Table 3. Bridges Natural Frequency |
|------------------------------------|
| Modal | 1 | 2 | 3 | 4 | 5 | 6 |
| Bridge Natural Frequency (Hz) | 6.668 | 7.62 | 8.474 | 9.855 | 10.073 | 12.005 |

| Table 4. Bridges Natural Frequency |
|------------------------------------|
| No | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 2xthe fan shaft frequency (Hz) | 2.179 | 2.396 | 2.614 | 2.832 | 3.05 | 3.268 | 3.486 | 3.704 | 3.921 | 4.139 | 4.357 |
To sum up, the blade frequency interference is the main cause of bridge vibration. The 3rd, 4th and 5th frequency multiplication are due to the fan blades to vibrate. During the high-speed operation of the fan, the fan blades to vibrate is caused the air resistance, thus forming a completely asymmetric state, resulting in integer frequency multiplication.

4. Conclusion
According to the above research, it is found that the main causes of bridge vibration are blade frequency, the third, fourth and fifth frequency multiplication of the fan. After hammering the bridge assembly, it is found that the blade frequency, the third, fourth and fifth frequency multiplication of the fan are place in the range of natural frequency of the bridge, so the vibration is large and the peak point is obvious. Therefore, in the design process of the bridge, the rigidity of the bridge should be controlled strictly, the natural frequency of the bridge should avoid the high frequency part of the blade frequency as much as possible, because the high frequency part generates large interference force. The above research provides a reference for the stiffness control standard in the later bridge design, so as to optimize the bridge structure and provide a basis for bridge design and vibration reduction.

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References
[1] Liu Lin, Bai Guoliang, Zeng Jinsheng, Xue Haijun, Vibration Study On The Big Diameter And Low-Frequency Operation Axial Flow Fan System In Direct Air Cooled Technique Thermo Power Plant, Steel Construction. 5 (2012) 21-25.
[2] Dou Ruijie, Qu Tiejun, Measurement on Response to Forced Vibration of Fan Bridge of Direct Air-cooling Fan System of Power Station, Journal of North China University of Technology. 1 (2011) 70-74.
[3] Qu Tiejun, Wang Xianyun, Zhang Mei, Experimental study on vertical oscillation forces of air cooling fan system in running state, Journal of Vibration And Shock. 32 (2013) 74-79.
[4] Qu Tiejun, Dou Ruijie, An Dong, Measurement of disturbing force caused by direct air-cooling fans of power station. 30 (2010) 80-83.
[5] Zhao Fei, Qu Tiejun, Research on Vibrational Characteristics of Fan Bridge Truss Under Multiple Air Cooling Fans Working Condition, Journal of North China University of Technology. 3 (2012) 68-71.
[6] Xiong Yinsheng, Fan bridge vibration response measurement and theoretical analysis, North China University of Technology, 2011.
[7] Zhou Quan, Research on Vibration of Direct Air-cooling Fan Tray, Wuhan University, 2014.