Experiment of the Influence of Dynamic Balancing Precision on Rotor Dynamic Behavior of 75KW Oil-free Turbo Blower

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Abstract. The principle and structure of the 75kW oil-free turbo blower is briefly introduced and the performance of gas foil bearings (GFBs) is tested. According to the test results, the lift-off speed of the gas foil journal bearings (GFJBs) using in 75kW oil-free turbo blower is about 4000rpm, and the gas foil thrust bearings (GFTBs) can provide at least 140N and 200N load capacity at 7200rpm and 9000rpm, respectively. The rotordynamics behavior of oil-free turbo blower is studied. Two proximity probes and speed sensor are installed to monitor the horizontal vibration displacement, vertical vibration displacement and shaft speed, respectively. And the vibration spectrum and the rotor axis orbit are analyzed. It was found that the maximum vibration amplitude of the rotor with dynamic balancing precision of G-1 was only 3.5\(\mu\)m, and no other low frequency other than low frequency caused by signal interference. The fundamental frequency vibration amplitude of the rotor with dynamic balancing precision of G-2.5 is larger when running stably, but there is no low frequency and high frequency vibration with higher amplitude. Shaft couldn’t lift-off with dynamic balancing precision of G-6.3 In general, oil-free turbo blower with two kinds of dynamic balancing precision rotors can operate well.

1. Introduction
A multitude of sewage-treatment plants have been established with the development of modern industrialization. In the process of sewage-treatment, a large part of the power losses is taken up by traditional blower employ oil-lubricated hydrodynamic bearings. Therefore, the oil-free turbo blower emerges as the times required. At present, it mainly includes turbo blower using magnetic bearings and turbo blower using GFBs[1]. Both have many common advantages, such as low friction, no pollution and reliable [2-5]. The GFBs are well received due to the complex control system and high costs of the magnetic bearings.

GFBs have been in use for 50 years, which has been widely applied [6-10]. GFBs are one of the key parts of oil-free turbo blower, mainly including GFJBs and GFTBs [11-14]. Up to now, there is a lot of research on the performance of GFBs. In 1983, Heshmat H. and Walowit J. A. established the foundation model of the bump foil equivalent to spring structure, and gave a calculation model [15, 16]. Later, the model and calculation methods were deeply studied [17-19]. Qi, S. Ho, Y. S. et al. Demonstrated the effects of the load, radial clearance and bearing radius on lift-off speed. The lift-off speed will increase with increasing load and radial clearance and decreasing bearing radius[20]. San

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Andrés, L., Chirathadam et al. presented the measurement of the friction torque and rotor lift-off speed. The results proved that the bearing friction torque increases with the static load and rotor speed[21]. Kim, T. H., Park, M. et al. studied the performance in optimizing maximum load capacity of GFTBs. The predictions show that the load capacity of the GFTBs increases with increasing rotor speed and decreasing minimum film thickness. And there is an optimum taper inlet height to maximize load capacity[22]. In 2018, Fu, G., Untaroiu, A. et al. established a 3D CFD model of a six pads GFTB and simulated the static properties. They predicted the relationship between friction torque and applied load and found that the predicted results of 3D CFD model was in good agreement with measurement[23].

Although GFBs has been studied since 1980s, more research on rotordynamics of GFBs has been carried out in recent 20 years. Many research teams began to present their studies on rotordynamic characteristic of oil-free turbomachinery using GFBs. Heshmat, H., Walton, J. F. et al. developed oil-free turbochargers and small gas turbine engines using GFBs and demonstrated the feasibility of GFBs application in 2000[7]. Walton, J. F., Heshmat, H. et al. presented the design and test program in oil-free turbo blower[24]. Zhou Q., Hou Y. et al. designed a high speed gas turbine test rig and carried out dynamic stability experiments. The relationship between vibration amplitude and rotor speed and rotor axis orbit at 125,413rpm were obtained[25]. Kim, T. H., Lee, Y. B. et al. studied the performance of the 75KW oil-free turbo blower. There were subsynchronous rotor motions at widespread frequencies due to insufficient load capacity of GFTBs. The rotor-GFBs system performance was improved by increasing the out diameter of GFTB[26]. Lee, J., Kim, Y. M. et al. presented rotordynamic performance of three types of journal bearing used in microturbomachinery. The rotordynamic stability characteristics was improved by reduced radial clearance of C-type bearing[27].

The rotor system often exist vibration when the oil-free turbo blower is running. There are many reasons for vibration, such as the imbalance of the rotor, the misalignment, the loosening of foundation fixed structure and so on. More noise, decreasing efficiency, and damaging parts will occur due to excessive vibration. Therefore, it is necessary to study the rotordynamics characteristic of oil-free turbo blower[28-31].

The film between foil and rotor is formed by principle of elastohydrodynamic lubrication. The film pressure isn’t enough to counter the gravity of the rotor due to low rotor speed. There will be dry friction between the rotor and bearing foil and the wear is extremely serious if the rotor speed doesn’t reach the "lift-off speed". The rotor will float and there is no direct contact between the rotor and GFBs when the rotor speed reaches the "lift-off speed". Therefore, the oil-free turbo blower is very energy-saving and reliable.

2. Description of oil-free turbo blower

The oil-free turbo blower is designed with the integrated design structure of permanent magnet synchronous motor, impeller, GFBs and inverter. As shown in Figure.1, the 75kW oil-free turbo blower is a kind of centrifugal blower in essence, which achieves the purpose of blowing by the continuous rotation of the impeller. The oil-free turbo blower is different from traditional blower using rolling bearing and it has the minimum operation rotor speed.

![Image 1](1081.png)

**Figure 1.** Physical diagram of oil-free turbo blower.
The film between foil and rotor is formed by principle of elastohydrodynamic lubrication. The film pressure isn’t enough to counter the gravity of the rotor due to low rotor speed. There will be dry friction between the rotor and bearing foil and the wear is extremely serious if the rotor speed doesn’t reach the "lift-off speed". The rotor will float and there is no direct contact between the rotor and GFBs when the rotor speed reaches the "lift-off speed". Therefore, the oil-free turbo blower is very energy-saving and reliable.

3. **Description of test GFBs**

The schematic diagram and physical diagram of test rig for GFJBs is shown in Figure 3 and Figure 4, respectively. The motor rotor speed and the friction torque of GFJBs are monitored in real time when testing performance of GFJBs. Simulate the weight of the rotor by loading the bearing with dead weight.

![Figure 2. Physical diagram of GFJBs.](image)

The inner diameter of GFJBs used for oil-free turbo blower is 60mm, and axial length is also 60mm, and Figure 2 is the physical diagram of GFJBs. Speed up the motor to 7200rpm, and the test data is shown in the Figure 5. The left Y-axis represents the motor speed and the right Y-axis represents the friction torque. The friction torque increases sharply because the lift-off speed of the GFJBs is not reached when accelerating the motor. At about 4000rpm, the friction torque decreases sharply and tends to be stable. Therefore, it can be judged that around 4000rpm is the lift-off speed of the GFJBs. Similarly, the friction torque will increase sharply when the motor speed reduced.

![Figure 3. Schematic diagram of test rig for GFJBs.](image)  ![Figure 4. Physical diagram of test rig for GFJBs.](image)

The schematic diagram and physical diagram of test rig for GFTBs is shown in Figure 6 and Figure 9, respectively. The motor rotor speed, the load applied to the GFTBs and the friction torque
are monitored simultaneously when testing performance of GFTBs. The load applied to GFTBs can be changed by adjusting the opening of valve.

![Figure 5. Friction torque versus rotor speed.](image)

![Figure 6. Physical diagram of test rig for GFTBs.](image)

The outer diameter and inner diameter of GFTBs used for oil-free turbo blower are 140mm and 69.5mm, respectively. The GFTBs has six pads, the angle of each pad is about 59 degrees and Figure.7 is the physical diagram of GFTBs. The GFTBs were tested at 7200 rpm and 9000 rpm, and the test data is shown in Figure.8. The test results show that the GFTBs can provide at least 140N load capacity at 7200rpm, and can provide at least 200N load capacity at 9000rpm.

![Figure 7. Physical diagram of GFTBs.](image)
4. Description of oil-free turbo blower
For 75KW oil-free turbo blower, the rotors with dynamic balancing precision of G-1, G-2.5 and G-6.3 are respectively assembled on the oil-free turbo blower for testing. Two Bently 3300XL proximity probes were installed to measure the horizontal and vertical vibration of rotor. In addition, the speed sensor was used to monitor rotor speed. The bearing parameters used in oil-free turbo blower and the rotor balancing precision are shown in Table 1.

| Parameters                     | value     |
|--------------------------------|-----------|
| Inner diameter of GFJBs/mm     | 60        |
| Axial diameter of GFJBs/mm     | 60        |
| Inner diameter of GFTBs /mm    | 70        |
| Outer diameter of GFTBs /mm    | 140       |
| Rotor dynamic balancing precision | G-1; G-2.5; G-6.3 |
First, the rotordynamics of oil-free turbo blower with dynamic balancing precision of G-1 is measured. Figure 10 shows the horizontal vibration spectrum, vertical vibration spectrum, and axis orbit of the rotor when the oil-free turbo blower is started and accelerated to 3000rpm. As can be seen from the coordinate values, the rotor axis orbit deviates from centre position. The rotor speed has not reached the "lift-off speed" of GFJBs, and the rotor has not yet floated. The lift-off speed is the indicator to judge whether the rotor and bearing surface enter the state of gas lubrication under specific load. The rotor speed does not reach the take-off speed, and the bearing does not enter the state of gas lubrication, causing the dry friction between the rotor and the bearing foil in direct contact. There are more clutter and higher noise in the spectrum, and the axis orbit deviates from centre position for the same reason. Dry friction exists between rotor and bearing foil. There is more clutter and higher noise in the spectrum.

![Horizontal vibration spectrum](image1)

![Vertical vibration spectrum](image2)

![Rotor Axis orbit](image3)

**Figure 10.** Vibration spectrum and rotor axis orbit with dynamic balancing precision of G-1 at 3000rpm.

Then the blower speed is driven to 12000rpm. Figure 11 shows the horizontal vibration spectrum, vertical vibration spectrum, and axis orbit of the rotor at 12000rpm. According to the rotor axis orbit and coordinate values, it can be seen that the axis orbit is basically in the cent centre of the coordinate system. Accordingly, rotor speed has reached the lift-off speed of GFJBs. The rotor is supported by the air film and floats, and hydrodynamic lubrication is formed between the rotor and the bearing foil. In the horizontal and vertical vibration spectrum, there are 2x, 3x and even higher frequency vibration, which are caused by misalignment. The amplitude of 3x frequency in the horizontal direction exceeds the fundamental frequency amplitude. However, it is only 3μm which has little effect on the stable operation of oil-free turbo blower. In addition, the rotor axis orbit is not regular and a low frequency about 50HZ appears on both spectrums.
Figure 11. Vibration spectrum and rotor axis orbit with dynamic balancing precision of G-1 at 12000rpm.

Figure 12 shows the horizontal vibration spectrum, vertical vibration spectrum and axis orbit of rotor at 19800rpm. Obviously, there are many high frequencies vibration in spectrums, but the 1X vibration amplitude is only 1.6μm. The reason for this phenomenon is that rotor balancing precision is very high, so the high frequency vibration amplitudes are relatively higher caused by misalignment of front and rear journal bearing.
Figure 12. Vibration spectrum and rotor axis orbit with dynamic balancing precision of G-1 at 19800rpm.

Figure 13 shows the horizontal vibration spectrum, vertical vibration spectrum, and axis orbit of the rotor when rotor speed is 25200rpm and working stably. According to the rotor Axis orbit and coordinate values, it can be seen that the axis orbit is relatively regular at this time, and the oil-free turbo blower is working well. The 1X vibration amplitude is the largest, about 2.5μm. There are fewer high frequency caused by misalignment and its amplitude is much smaller than 1X vibration amplitude. Additionally, the sub-synchronous, 50HZ and 200HZ is also appeared, which does not change with the increase of rotor speed. Therefore, it can be judged that this sub-synchronous, 50HZ and 200HZ may be caused by electromagnetic interference instead of rotor system problems.

(a) Horizontal vibration spectrum    (b) Vertical vibration spectrum    (c) Rotor Axis orbit

Figure 13. Vibration spectrum and rotor axis orbit with dynamic balancing precision of G-1 at 19800rpm.
Figure 14 shows the bearing foil wear after the oil-free turbo blower test. It can be found that the foil coating of GFJBs is slightly worn, and the foil coating of GFTBs is almost not worn. This is because the gravity of rotor is applied to the GFJBs and dry friction is relatively serious during starting and stopping of the oil-free turbo blower.

Similarly, the rotordynamics of oil-free turbo blower with dynamic balancing precision of G-2.5 and G-6.3 are measured. Figure 15 shows the horizontal vibration spectrum, vertical vibration spectrum and axis orbit of rotor when rotor speed is 25200rpm and working stably. It can be seen that the fundamental frequency vibration amplitude has reached 12μm, which is much larger than dynamic balancing precision of G-1 because of the mass imbalance of the shaft. The amplitudes of other frequencies in rotor axis orbit and spectrum are not obvious due to the large fundamental frequency amplitude.

Figure 15. Vibration spectrum and rotor axis orbit with dynamic balancing precision of G-2.5 at 25200rpm.
However, when the dynamic balancing precision increases to G-6.3, blower shaft couldn't lift-off because the hydrodynamic film cannot be formed when imbalance force is too large. Top foil coating of both journal bearing and thrust bearing are wear out, as shown in Figure.16.

![Image](image_url)

**Figure 16.** Journal bearing and thrust bearing wear after test with dynamic balancing precision of G-6.3.

5. Conclusion
The test rig for bearing test was built and bearing performance was tested. The lift-off speed of GFJBs used in the oil-free turbo blower is about 4000rpm. The GFTBs can provide at least 140N and 200N load capacity at 7200rpm and 9000rpm, respectively.

The rotor dynamics of oil-free turbo blower was measured with different dynamic balancing precision. It indicated that the oil-free turbo blower with high dynamic balancing precision can operate very well while shaft cannot lift off with G-6.3 dynamic balancing precision. In general, dynamic balancing precision of G-2.5 can be adopted if cost saving is considered.

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