

REGULAR ARTICLE

Experimental research on cage dynamic characteristics of angular contact ball bearing

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Abstract. The dynamic performance and life of the precise bearing, even abnormal operation and early failure are affected directly by the complex and unstable motion of the cage. Based on the cage dynamic performance test device with controllable motion of inner and outer rings, respectively, the dynamic characteristics of the cage were studied under different rotating speeds and loads, while inner ring rotated with outer ring fixed and inner–outer rings rotated reversely. Then the trajectory of the cage mass center was drawn through experimental study. The three-dimensional space motions of cage reveal that, when only inner ring rotates, the trajectories of cage mass center are approximately circular under axial load, and the amplitude of the axial displacement raises with the increase of the rotation speeds. With the increase of radial loads, the cage mass center trajectories are shaking from a circle to a small area on the side of the bearing center. When the inner–outer rings rotate in the opposite direction, the rotation speed of the cage is greatly reduced, and the mass center trajectories of the cage oscillate irregularly on side of the bearing center. As the relative rotation speed of rings increases, the axial displacement fluctuation enlarges. With the increase of the radial loads, the axial fluctuation decreases.

Keywords: Angular contact ball bearings / dynamic characteristic / cage whirl / test rig

1 Introduction

With the development of aerospace and equipment manufacturing, angular contact ball bearings are the essential components of aero engines and precision machine tools, their accuracy, longevity, and reliability are critical to the entire equipment. The cage is the main research object of the dynamic characteristics of the rolling bearing. The instability of the cage will cause the friction torque of the bearing to fluctuate, the friction and wear will be increased, thus the whistling will occur, even the cage will break, which will cause bearing failure or spindle bearing jam and catastrophic consequences [1–3]. Since 1960s, people began to notice the dynamic performance of high-speed rolling bearings and mainly studied the stability of the cage.

Due to the special position of the cage in the bearing and the transient nature of the force, the current motion analysis is mainly based on a dynamic model. On the one hand, the equations of motion are established based on the geometric structure and the motion relationship between the bearings to obtain the movement law of the parts. On

the other hand, a general dynamics analysis software is used to establish a model based on the parameters of the bearing, set the working conditions to analyze and solve, then the post-processing software is used to extract the motion characteristics of each part. Gupta [4–6] established a complete dynamics model of all bearing parts, which can simulate the transient motion characteristics of bearing parts, in addition, ADORE, a dynamic analysis program for rolling bearings that considers factors such as geometry, lubrication, cage structure, and materials, was developed, and the effect of load and speed on the mass center movement of the cage was experimentally investigated to verify the simulation results of the ADORE program. Gentle and Pasdari [7] found that the friction between the ball and the cage, the torque generated by the cage rotation, the temperature of the bearing, the lubricant content and viscosity, and the structural dimensions of the cage have an effect on the stability of the cage through experiments. Kingsbury [8,9] used the ratio of the angular velocity of the cage mass center to the ball revolution speed as a criterion for determining the stability of the bearing, proposed the eddy model of the angular contact ball bearing, measured and identified different types of cage whirling, and divided it into stability and instability. Stevens [10] studied the influence of the instability of the

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angular contact ball bearing cage on the frictional torque through experiments about different lubricant and cage geometrical parameters. Boesiger et al. [11] experimentally studied the influencing factors of cage instability, and analyzed the relationship between cage whirl frequencies. Makoto [12] analyzed the effects of working temperature, viscosity of lubricant, preload, rotational acceleration, and cage unbalance on the cage movement through tests, and studied the vibration and movement of ceramic ball bearing cages for spindles of machine tools. Kazuo et al. [13] adopted a method of widening the test bearing cage to install sensors in the axial and radial directions to measure the trajectory of the cage. The influence of the vibration and lubrication parameters of the cage on the cage whirling was studied. The test scheme requires complicated installation of the sensor and requires additional changing the cage structure. Huang [14] proposed to record the radial vibration of the cage by using two laser sensors, and introduced the orbits of cage mass center. But its test speed was low and changed the outer ring by cutting grooves. Wen et al. [15] and Han et al. [16] developed cage dynamic performance testing machines for different bearing sizes and operating conditions, and studied the effects of load, speed, and cage unbalance mass on cage center motion. Abele et al. [17] and Yang et al. [18] used high-speed cameras to continuously take pictures of running bearings. According to the marker points on the cage, the rotational speed and centroid trajectory of the cage can be obtained through image processing algorithms. Palladino et al. [19] used the same photographic method to analyze the effect of different clearance ratios and axial forces on the stability of the cage. This method can accurately measure the movement of the cage in the radial plane without making any changes to the cage, but only measure the radial motions of the cage at the same time.

In summary, because of the complex movement of the bearing cage in space, its motion measurement is difficult, the existing research on the dynamic characteristics of the cage mainly focuses on the dynamic model of the cage, the failure mode, and the centroid trajectory. Due to the limitation of motor or spindle speed and sampling frequency of the displacement sensor, the rotational speed of the tested bearing cannot be higher, and the radial displacement measurement of the cage needs to change the bearing structure, while there are few experimental studies on the non-contact measurement of the dynamic performance of the cage without changing the bearing structure.

Therefore, in view of the deficiencies of the current cage dynamic characteristics testing machine, a new type of high-speed angular contact ball bearing cage dynamic performance test rig is developed by our research group, the rotational speed of the inner and outer rings of the bearing are controlled by two motors, at the same time, the rotational speed of the cage is reduced by the inner-outer rings rotated reversely, and the axial and radial displacements of the cage are simultaneously measured by the vertically arranged laser line displacement sensors, then a centroid trajectory of the cage is drawn, thereby the research on cage dynamic characteristics can be realized by using the experiment apparatus.

2 Experimental rig and method

2.1 Test rig

A test rig is specially developed to measure the cage dynamic characteristics of a ball bearing in three dimensions, and different conditions are analyzed, such as the rotation speed, external radial load, and the rotated ring.

The bearing test rig is shown in Figure 1, the test bearing's gravity is along the axial direction, which consists the drive, transmission, load device, and measuring mechanisms. One motor is connected to the inner ring of the bearing through the shaft 1 and coupling, the other motor drives the outer ring of the tested bearing through the shaft 2, the friction wheel 2 and loading wheel. The loading wheel and the friction wheel 1 installed in the outer ring of the test bearing form friction drive system, the radial load is applied to the bearing by the friction wheel 1, which is pressed by the spring and is arranged in a triangle shape in Figure 2. The tested bearing is an angular contact ball bearing mounted in pairs and the axial load is adjusted through the spacers. Located at the outer end of the test bearing, perpendicular laser sensors applied to measure the axial and radial displacements of the cage center as shown in Figure 2. During the test, by adjusting the rotation speed of two motors, on the one hand, the inner and outer rings of the tested bearing can be rotated in the reverse direction to obtain higher relative rotation speeds, meanwhile, the rotating speed of the cage reduced greatly and can be measured more easily; on the other hand, it is also possible to fix one ring and rotate the other ring to study the motion characteristics of the cage. Without modification of the bearing, the cage movements in three dimensions are measured simultaneously.

2.2 The calibration and measurement of test

During assembling, to make sure the motor and bearing house are mounted on the same base, the dial gauge is used to test the radial variation when the drive shaft rotates. The centering of the drive shaft and the spindle is fine-tuned through the set screws. This ensures that the axis of the motor spindle is aligned with the axis of the bearing support. It is also necessary to ensure that there is no deviation between the two bearings axes and the friction wheel so as to achieve stable transmission motion. The axis of the two mutually perpendicular laser line displacement sensors in the measuring device is aligned with the axis of the tested bearing so as to measure the axial and radial displacement of the cage at different positions of the tested bearing.

LJ-G015K, the trigger interval is 3.8 ms, the effective axial displacement is 15 ± 2.3 mm, and the effective range of the laser line is equally distributed 800 points of invalid and effective points, with an interval of 0.01 mm, axial repetitive accuracy is 0.2 and $2.5 \mu\text{m}$ in radial. Under the effective axial distance, the data on the laser line changed

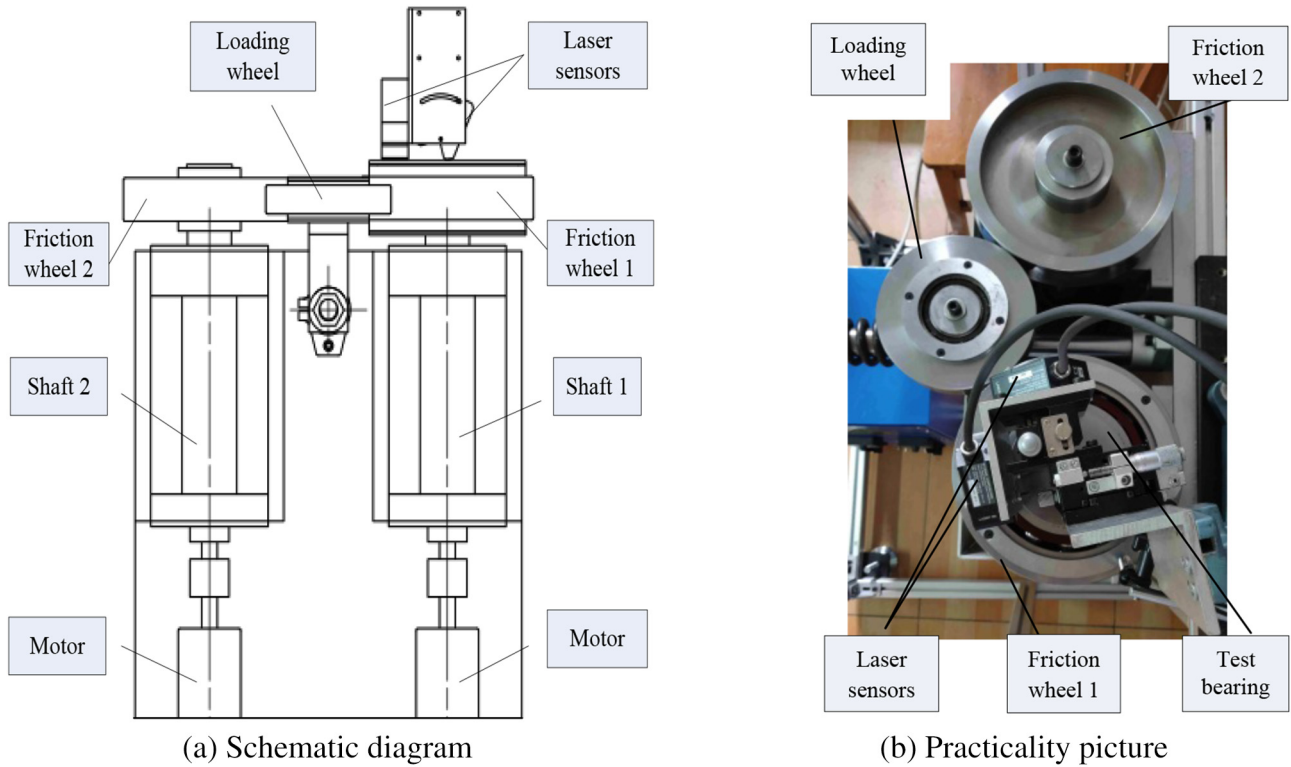


Fig. 1. Bearing test rig.

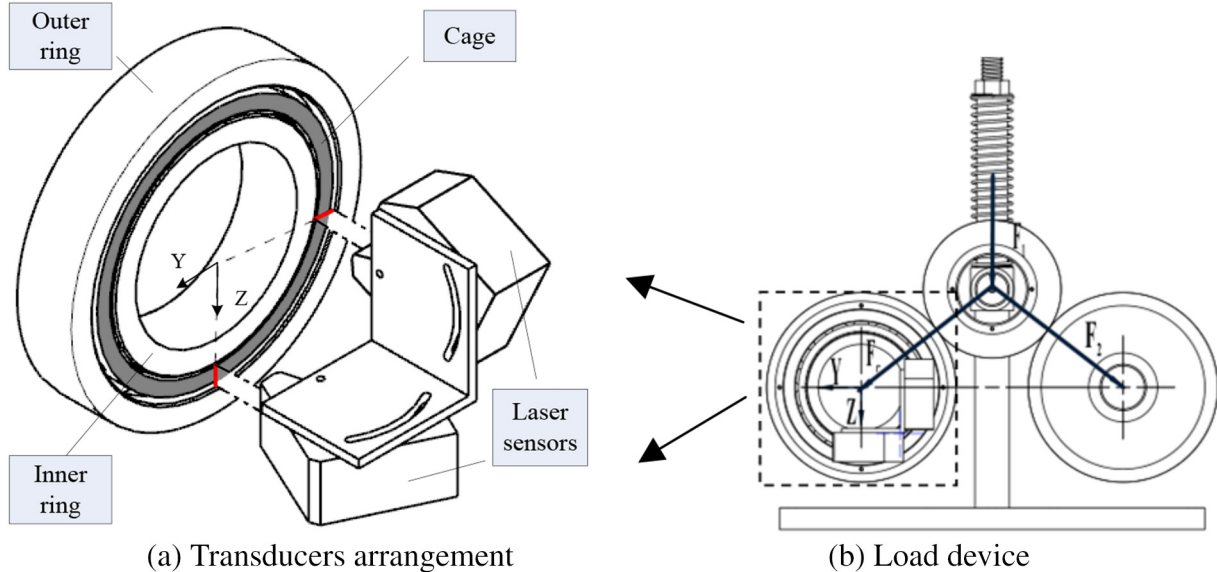


Fig. 2. Loading and measurement method.

with the motion of measured subject, as the number of invalid and effective data collected by the software on the computer, thus the displacement can be obtained from data extraction.

In order to record the movement of the cage effectively, so adjusting the position of the laser sensors to ensure that the movement of the cage is within the effective range of the sensors. Therefore, based on the cage outer diameter and as

the reference, the effective measurement boundary of the sensor is larger than the cage outer diameter by 2–3 mm. And the intersection of two laser lines is collinear with bearing center line.

In addition, for the calibration of the laser sensors, two perpendicular laser lines are irradiated on the cage shown in Figure 2a. Changing the position of the cage from position 1 to 2 in Figure 3: move 0.618 mm vertically and

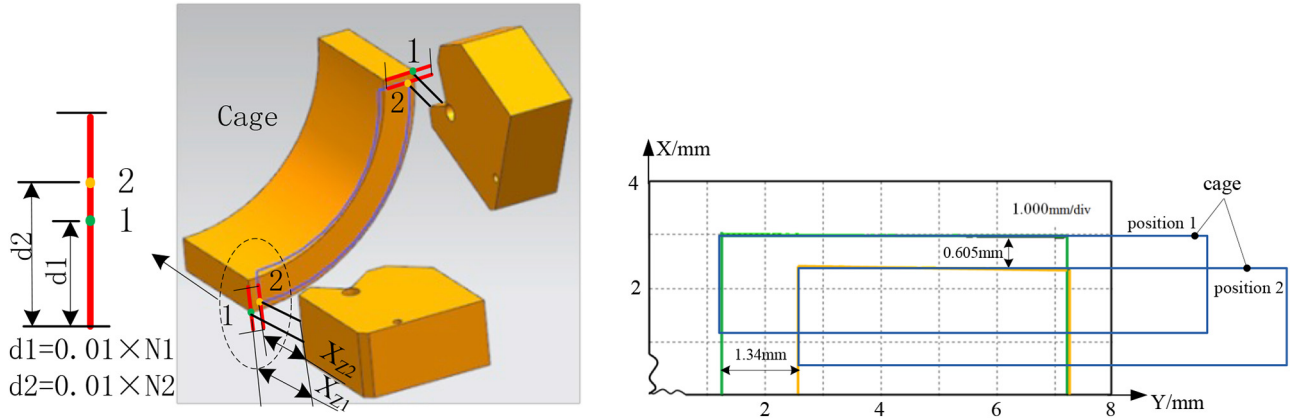


Fig. 3. 3D measurement method and calibration of the laser sensor.

Table 1. Geometrical parameters of an angular contact ball bearing 7220C.

Parameters	Value	Parameters	Value
Ball diameter	25.4 mm	Cage inner diameter	128 mm
Bearing outside diameter	180 mm	Cage outer diameter	145 mm
Bearing inside diameter	100 mm	Pocket clearance	0.6 mm
Initial contact angle	15 deg	Cage width	31 mm
Inner curvature radius	13.210 mm	Number of balls	14
Outer curvature radius	13.221 mm	Cage guiding land diametric clearance	2 mm

Table 2. Experimental conditions.

	Rotated ring	Speed (r/min)	Radial load (N)
1st	IRR	500~2000	0~150
2nd	IOR	500~2000	0~150

1.38 mm horizontally. Set position 1 as the reference and record it, extracting and calculating the number of invalid data of position 1($N1$) and 2($N2$). It turned out that 0.605 mm from X_{Z1} to X_{Z2} in axial, and 1.34 mm from $d1$ to $d2$ in radial. The same way of calibration to another sensor. From the data, it can also be seen that the error between the actual calibration data and the software display data is little for the test bearing.

With two sensors arranged vertically, the radial motion can be collected. One collects the axial (X_Z) and vertical radial displacement (Z), the other collects the axial (X_Y) and horizontal radial displacement (Y), axial motion adopts the average value recorded by the sensors, so the laser sensors can effectively record the three-dimensional motions of the cage center at the same time.

3 Experimental condition and bearing specimen

This experiment adopts the laser line displacement sensor for data acquisition, taking into account the size and

installation position of the sensor itself, angular contact ball bearings 7220C are designed as test bearing. The geometrical parameters are listed in Table 1. In addition, the cage is made of cloth Bakelite, the inner, outer ring, and ball material is GCr15 high temperature bearing steel. The cage is inner ring guidance, and axial preload 100 N is applied by the adjusting spacer. In order to analyze the cage characteristics under different conditions and provide contrast, the study mainly focused on the cage mass center motion under different cases of the inner ring rotated with fixed outer ring (IRR) and inner and outer rings rotated reversely (IOR), as shown in Table 2.

4 Results and analysis

The movement of the cage mass center is affected by the rotating speed, load and the impact of collision and friction with the ring and the rolling element. Therefore, the effect of the rotation speed and the external radial load on cage mass center whirl motion is studied. The Y and Z displacements represent the displacement of the cage mass center in the radial plane, respectively, and the X displacement is the axial motion, as shown in Figure 2.

4.1 Inner ring rotated with outer ring fixed

The trajectories of the cage mass center and axial motion displacements in the first case listed in Table 2 are illustrated in Figures 4 and 5.

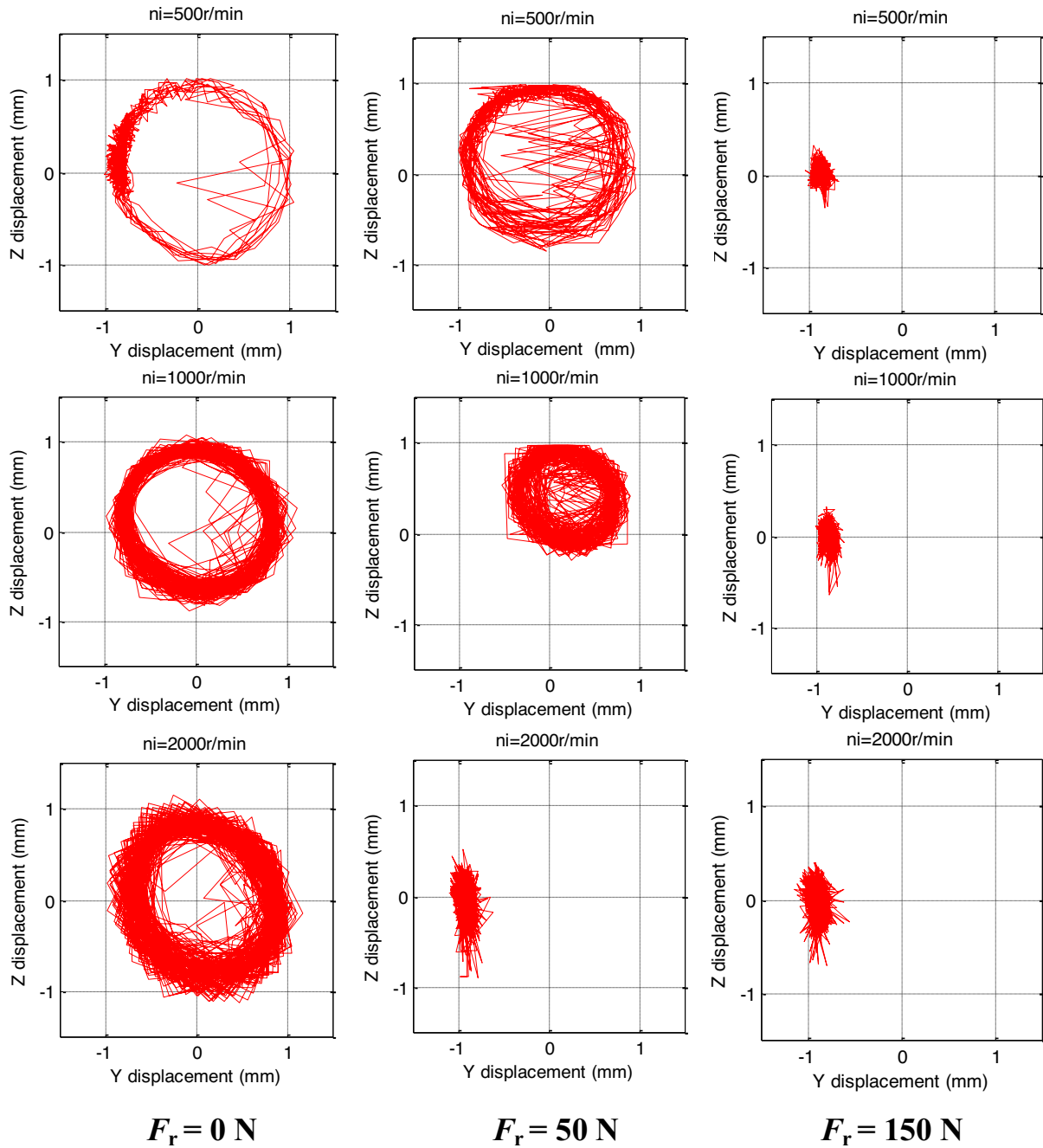


Fig. 4. The trajectories of cage mass center under different radial loads.

When the condition is inner ring rotated with fixed outer ring, the trajectories of the cage mass center are illustrated in Figure 4 and axial motion in Figure 5, in which the rotating speeds are 500 ($n_i = 500$, $n_o = 0$) r/min, 1000 ($n_i = 1000$, $n_o = 0$) r/min, and 2000 ($n_i = 2000$, $n_o = 0$) r/min under different radial loads, n_i and n_o are the rotation speed of inner and outer rings, respectively, and processing the axial motion into difference between X_{\max} , X_{\min} and standard deviation. It is shown that the trajectories of the cage mass center are similar to a circle, and the whirl radius of the cage motions is equal to the

guiding radius clearance. On increasing the rotating speeds, given that the limitation of the sampling frequency of the laser sensor, the data collected in one revolution of the cage are reduced to form a polygonal centroid trajectory, and the axial movement amplitude is increased from 0.2755 mm in 500 r/min to 0.4455 mm in 2000 r/min under axial load. The test bearing is inner race guidance, higher rotating speeds of inner ring bring out greater speed of cage, the centrifugal force of the cage increased under the rotation motion, larger interaction forces such as contact and collision interaction between

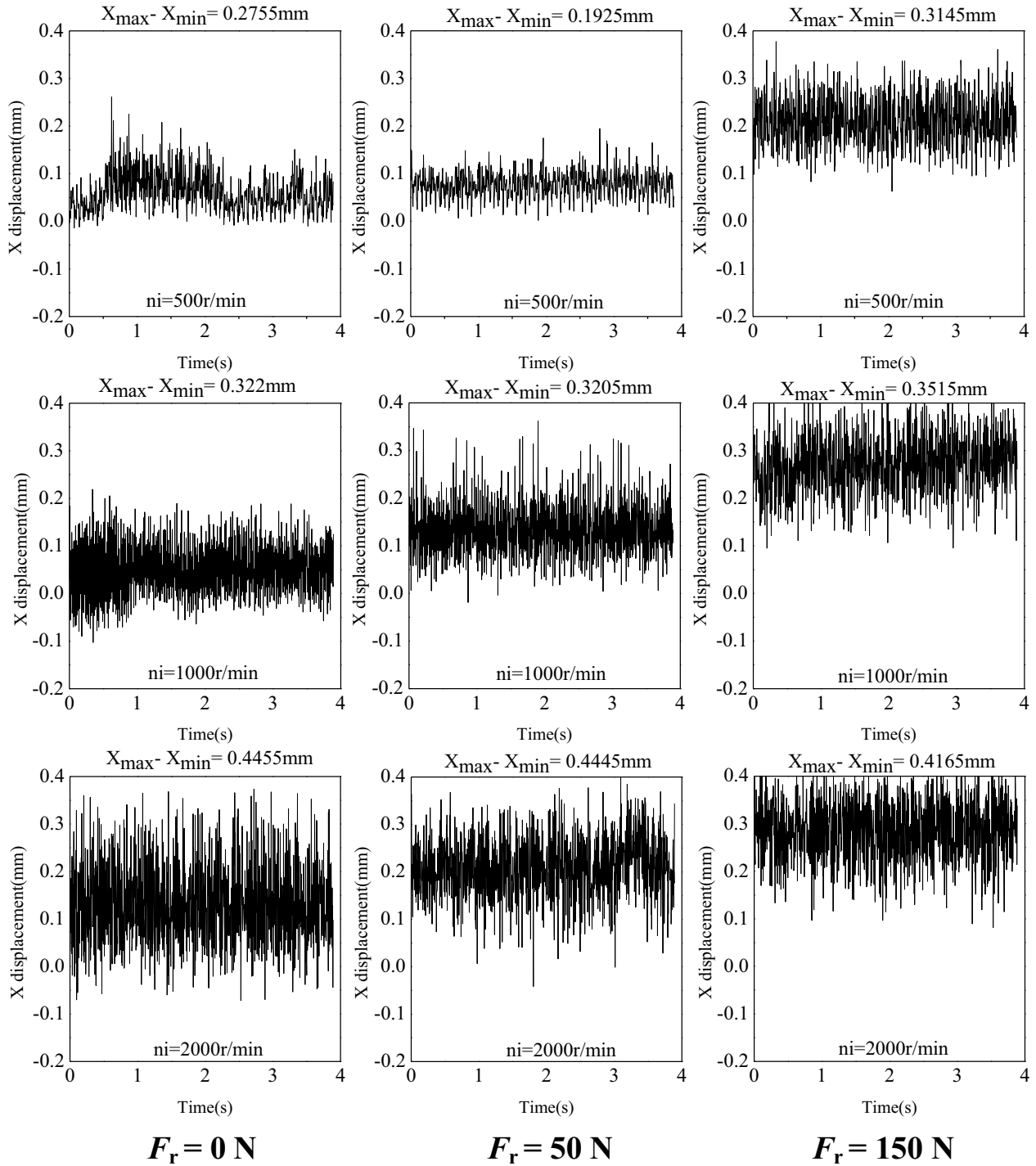


Fig. 5. The axial displacements of cage mass center under different radial loads.

cage and balls and between cage and inner ring generate, so the range by cage center area of whirl trajectories and the fluctuation by difference of axial displacement enlarged.

Indicating that the increment of radial loads can bring trajectories of cage mass center from regular to irregular, and the whirl radii of cage motions are diminished to form

the patterns at one side of the bearing center, which is consistent with the experimental investigation in Wen et al. [15], and it is also consistent with observation that the cage is biased to one side during the test, and the variation of axial fluctuation range is smaller. As is known that the increasing external radial loads can make the contact loads between balls and rings become unevenly distributed,

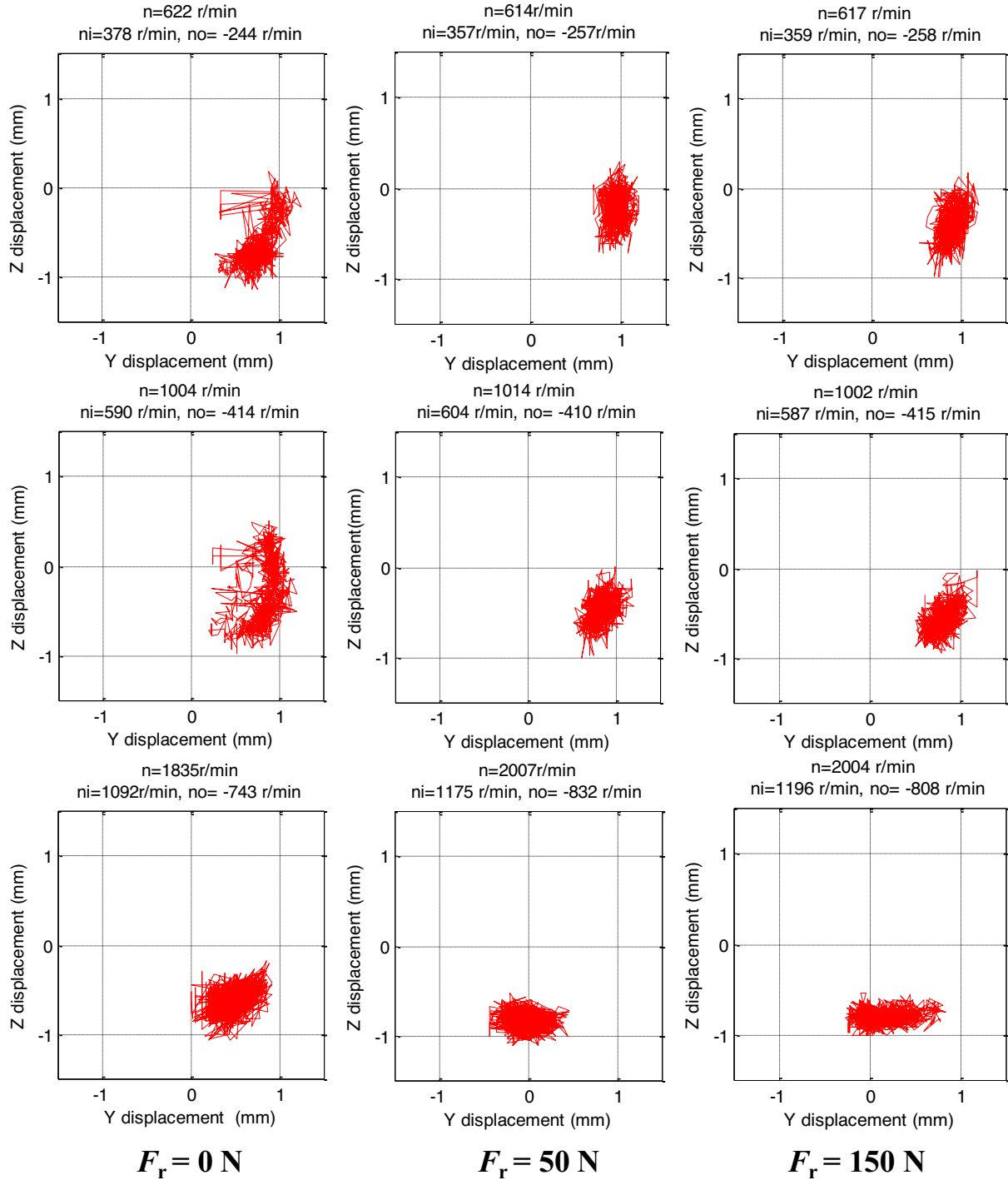


Fig. 6. The trajectories of cage mass center under different radial loads.

uneven load distribution will differentiate the traction forces of balls, to which lead the speed fluctuation of balls. On accounting of the speed of balls vary constantly, the frequency of collision between the cage pocket and balls will enhance, the resultant force of cage changes over and over again at the same time. It brings out the complicated and irregular whirl trajectories and the decrease of whirl radii of cage motion.

4.2 Inner and outer rings rotated in opposite direction

The trajectories of the cage mass center and axial motion displacements in the second case listed in Table 2 are illustrated in Figures 6 and 7.

When the condition is inner and outer rings rotated reversely, the trajectories of the cage mass center are showed in Figure 6 and axial motion in Figure 7,

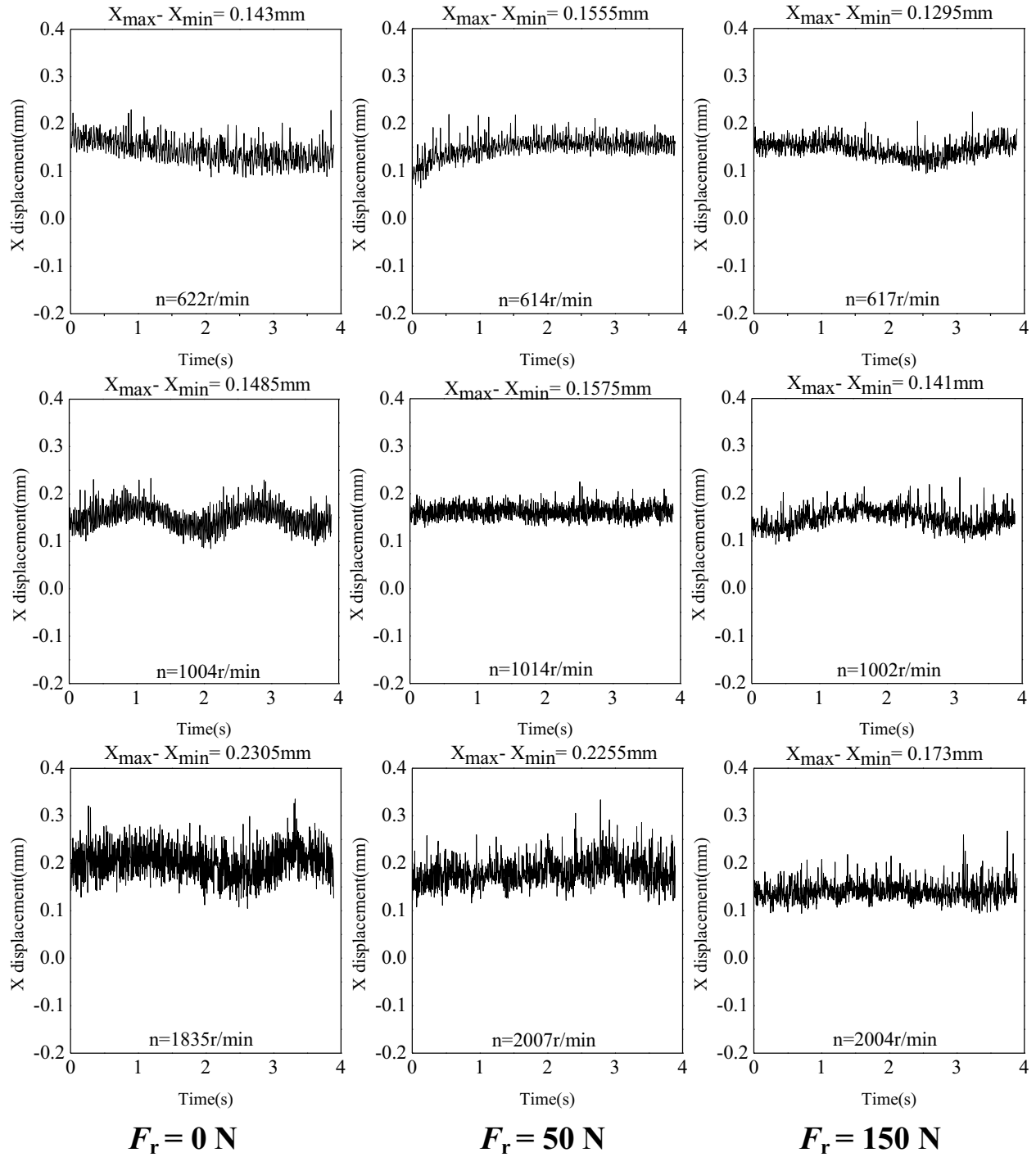


Fig. 7. The axial displacements of cage mass center under different radial loads.

which the actual measured relative rotating speeds (n) are marked in the picture under different radial loads, respectively. On accounting of revolution speed of cage is mostly decreased, the whirl trajectories of cage present complicated patterns, which appeared swaying around one side of the bearing center, and with the increase of rotation speeds, the interaction forces between cage and balls got enhanced, the axial displacement fluctuation

become large from the difference between X_{\max} and X_{\min} , about 0.143, 0.1485, and 0.2305 mm under different speeds.

With the external radial loads increasing, the change of cage mass center trajectories is not obvious. Due to the cage speed reduced greatly, the resultant force on cage is small, the axial displacement fluctuates little until the higher rotation speed.

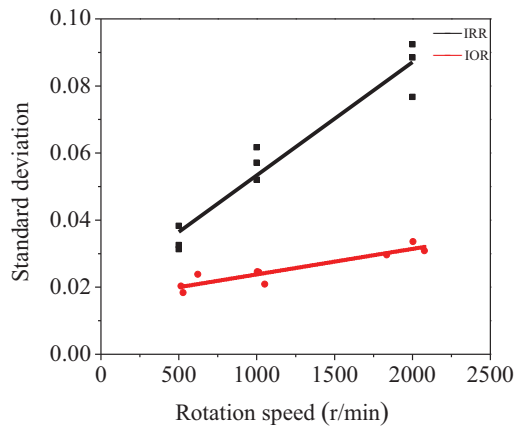


Fig. 8. The standard deviation of axial displacement in axial load.

Comparing the two conditions under three times tests, the whirl trajectories of the cage mass center vary from well-defined to irregular under two conditions, which only inner ring rotated with outer ring fixed, inner and outer rings rotated in opposite direction. By calculating the standard deviation of axial displacement in axial load under different speeds of three times test work respectively and then fitting the standard deviation in curve, it is shown in Figure 8, the cage fluctuation in IRR is larger than that in IOR. Because of the frequent collision between the cage and the guided ring and the frequent interaction between the cage pockets and the balls, a circular centroid trajectory is easily formed when the cage is properly high speed. Correspondingly, the cage rotation speed is greatly reduced to zero under the opposite direction of inner and outer rings, the revolution speed of the balls is significantly reduced similarly, so the impact between the cage and the balls is weakened. And the cage pocket clearance is less than the guiding clearance, the resultant force of the cage reduces and the friction force with the ball is the main resource, thus the cage forms a disordered movement pattern, and the axial displacement of the cage is smaller.

5 Conclusion

Through adequate and extensive experimental works on the bearing cage test rig, the dynamic characteristics of cage in three dimensions with rotated inner ring-fixed outer ring (IRR) and inner-outer rings rotated reversely (IOR) under different speeds and external radial loads are investigated, and the conclusions are drawn as follows:

- (1) The scheme of cage dynamic characteristics in bearing cage test rig is feasible, without modification in the test bearing, the cage motion in three-dimensional space can be measured by two laser sensors in vertically arrangement.
- (2) Under axial load, a regular circle whirl trajectory is formed at the IRR condition, the cage will keep a

constant speed, and the whirl radii are equal to the cage-ring guiding radius clearance. An irregular pattern on the side of bearing center is exhibited at the IOR condition, the cage rotation speed is closed to zero.

- (3) For only inner ring rotated (IRR), the increase in the rotating speeds makes the trajectories of cage mass center more regular and enlarges the axial motion range; on increasing the external radial loads, the trajectories of cage mass center transform from regular circle patterns to irregular ones that shake on the side of the bearing center.
- (4) For the case of IOR, the cage mass center trajectories are less changed by rotational speeds and radial loads. The increasing relative rotating speeds make the axial displacement fluctuation enlarged; with the increment of external radial loads, the axial fluctuation diminished.

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