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Experimental analysis of Axial load internal circulation ball screw pair of friction torque and the impact

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Abstract: According to the working principle of the ball in and out of the race in inner circulation and external loop, analyzed under the action of axial force of the ball in and out of the influence of the raceway for the ball screw friction resistance, due to ball in rail friction drag is small, that the inner loop no loss as external loop ball friction energy in the circulation pipe, friction torque variation of the ball in and out is small. Experimental results show that the inner loop of the ball screw's friction torque increases with the increase of rotational speed, but the amount of friction torque fluctuation is small, under the screw speed, the axial force has certain influence for inner loop ball screw's friction torque fluctuation and ball impact, but under the relatively high speed is not obvious of on the two.

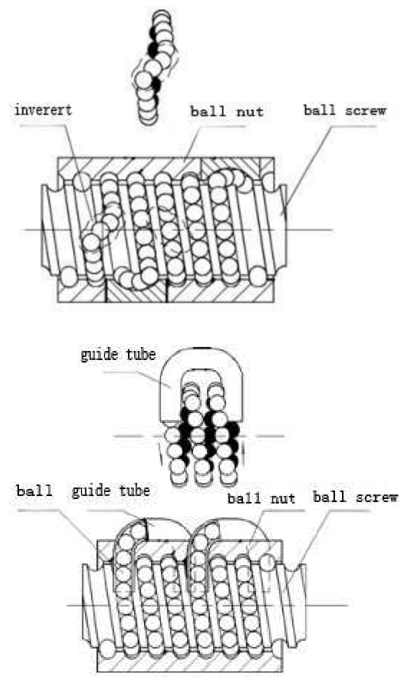


Fig.1 The diagram of ball screw pair of inner loop and outer loop

0 Preface

As a key component of mechanical transmission, ball screw assembly has been widely used by its high speed and low damp movement characteristics. In addition，it has a great impact to mechanical motion properties and dynamic behavior in the practical application. The fluctuations of its friction moment will have a direct impact on the stationarity of the driving system. In the case of low speed and light load, especially at the occasions that it demands strict stationarity situations, the influence of ball screw pair friction moment to the products comes out by the way of surface roughness on the surface of the products. Therefore, it has the extremely vital significance to make sure the rules and factors of its fluctuation of friction moment on making reasonable use to the ball screw assembly. Based on experimental study, the thesis analyzes the fluctuation characteristic of the ball screw assembly friction torque under different modes of circulation, and it focuses on influence factors of its friction moment as well as fluctuation factors under different axial force and under inner loop mode.

1 The analysis of ball friction torque under inner and outer circulation

There are two kinds of ball circulation on ball screw assembly--outer loop and inner loop.The outer loop is that the balls disengage from screw in the returning process of circulation; the inner loop mode is that the balls always keep contact with the surface of screw when circulating. As shown in figure 1, within the side face hole of the nut, it is equipped with an inverter to connect the adjacent rollaway nest, which is used to conduct balls to pass the top of thread to get into the adjacent rollaway nest so that it forms a circulation loop. Generally, one nut is equipped with 2 to 4 reversers, and they distribute uniformly along the nut.

1.1 The fluctuation analysis of ball friction torque under outer circulation

As to the outer circulation ball screw，it has a preloaded force from screw at the entrance of inverter rollaway nest, and then the ball has to overcome screw friction force to go into the raceway, that is to say it needs a force F_t' on the entrance ball. And the force is provided by the ball at the exit, so there will be a huge friction force at the exit of screw, and then a fluctuation of screw friction torque comes out.

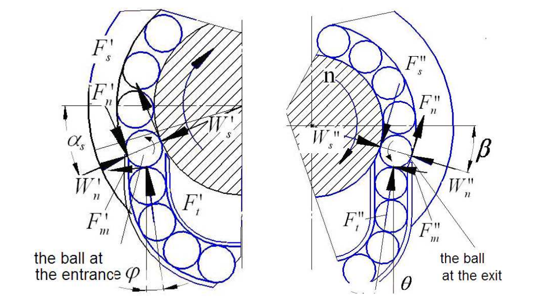


Fig.2 The diagram of force of screw when ball rolls in and out

As is shown in figure 2, the front ball gets a force F_t' from the rear one at the entrance, and in order to satisfy the condition that there is no skid on the raceway, it must be a downward force at the nut contact point. And under the same lubrication and friction conditions, the contact point between ball and screw will have a slide, and then the friction force reaches the maximum at this point. As is described in the figure, the rear ball pushes forward the front ball, and provides a driving force to make the front ball go into its rollaway nest.

In the screw rollaway nest, the movement of ball is the result that the ball behind pushes forward the front ball. As is shown in figure 2, in the direction of movement, the ball at the outlet of raceway was reacted resistance by two resistance, one of which is rolling friction that engenders when the ball rolls along the rollaway nest (not shown in the figure), the other is the reaction force F_t'' engendered by the front ball. The resultant of these two forces keeps a balance with F_s'' in theory (F_s'' is the force between the rear ball and the front ball at the outlet), the force F_s'' makes the ball convert from pure rolling to sliding, thereby, and it affects the friction between the ball behind and the raceway of screw.

When the ball goes into the raceway, the friction torque fluctuates in the form of a semi-sinusoidal variation, so the screw friction torque that comes from the friction of the ball at the entrance is as follows:

$$M_o = \sin\left(\frac{\pi t - n\omega_b}{\tau}\right)\left(F_{ta}''r_{d1} + M_{ba0}\right)\text{；} \qquad \left(0 \le \frac{\pi t - n\omega_b}{\tau} \le \tau_1 = \kappa_{\mathrm{m}}\pi\right)$$

$$M_o = M_{o1} + M_{ba0}\text{；} \qquad \left(\tau_1 \le \frac{\pi t - n\omega_b}{\tau} \le \tau_2\right) \qquad (1)$$

$$M_o = (M_{o1} + M_{ba0})\cos\left(\frac{\pi t - n\omega_b}{\tau}\right)\text{；} \qquad \left(\tau_2 \le \frac{\pi t - n\omega_b}{\tau} \le \frac{1}{\omega_b}\right)$$

τ is a half-sine pulse constant associated with preload and speed, ω_b is a frequency of the ball that goes in and out the raceway, M_{ba0} is the screw friction torque of a single ball axial, which is engendered in the raceway under the axial force.

For the double-nut ball screw, the left nut has no flange but manufactures thread, and it was fixed by two round nuts. The right one has the flange at its outer end. when it need a preload, just tighten the round nut inside to eliminate the gap, then use the outside round nut to drop lock.

When the left nut of the ball screw bears the working load, the actual force of the right nut becomes larger compareed with its original preload, while actual force of the left nut is reduced. Thus, the friction of the left and right sides is different when the balls roll on the rollaway nest. When the axial load increases, the friction of the left and right sides has a different incremental value. This shows that, with the axial load increasing, friction torque of the screw increases, and the fluctuations of friction torque is different at different locations.

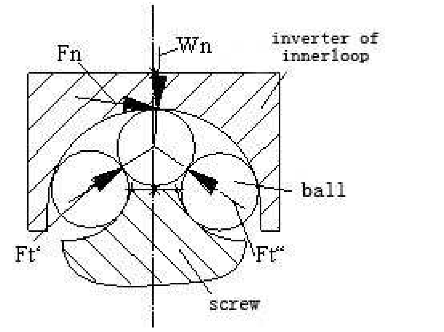


Fig.3 The diagram of force when ball rolls in raceway of Inner loop

1.2 The fluctuation analysis of ball friction torque under inner circulation

For the inner circulation of ball screw, as is shown in figure 3, the balls move through the inner circulation inverter from right to left and accomplish their reversing motion. It is the same with the outer circulation, the ball has to overcome screw friction force to go into the raceway because of screw's pre-tighten purpose, that is to say it needs a force F_t' to react on the entrance ball, and the force is provided by the ball at the exit. In the figure 4, the transition ball in the middle is engendered by two force, one is F_t'' that is from the ball at the exit, and the other is F_t' that is from the ball at the entrance. And the resultant force provides the power that makes the ball go across screw vertices. Formula (2) shown above is also applied to moment calculation of inner circulation.

For the two kinds of Cycle mode, in addition to structural differences, the friction that is engendered when the balls roll on the raceway is also different. For the ball screw of outer circulation way, when the balls go through the inverter rollaway nest, the moving distance is longer, so the friction of rollaway nest can not be ignored, and thus the force F_t'' is required to be bigger. As for the ball screw of inner circulation mode, due to the balls makes a short distance in the inverter rollaway nest, the rolling friction is small, and the corresponding force F_t'' is also small, for this reason, fluctuation of friction torque is small.

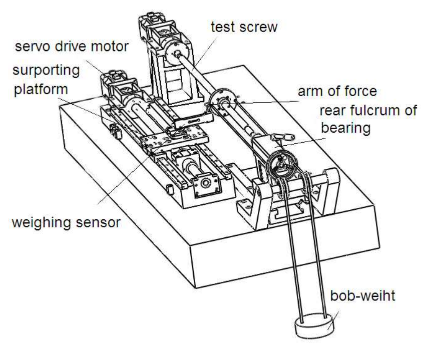


Fig.4 Ball screw pair test system at the action of axial force

2 The friction torque experiment of ball screw pair under axial force

As is shown in figure 4, the ball screw withstands the axial force caused by the additional weight, in order to maintain the balance of ball screw under the axial force, the form of a double cable is adopted to connect the additional weight. There is a arm fixed on the ball screw nut, and this arm will pass the friction that generated when the screw rotates to the load cell. The load cell is mounted on the support platform, and the support platform maintains synchronous movement with the arm when the screw system runs, all above ensure that the friction generated when the screw rotates can be acted on the load cell continuously. The test screw and support platform are driven by two AC servo motor independently, and they keep pace when they run. The ball screw driving the support platform adopts a precision grinding screw to ensure the system runs smoothly and accurately.

3 Inner loop ball screw friction torque test data analysis

3.1 The relationship of velocity and friction moment

Lots of factors affects the value of the friction moment and it shows extremely complex features in tests, but the comprehensive friction moment can be obtained from test data. The overall frictional resisting moment of screw increases with the increase of its speed by taking the test data's mean value (as is shown in Figure 5). That has something to do with the friction condition of screw.

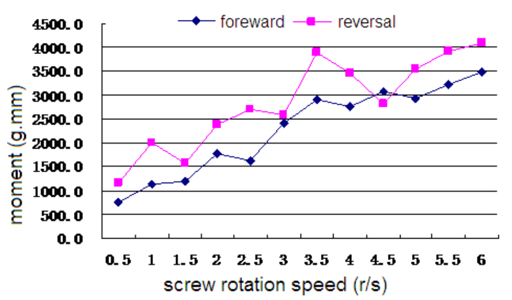
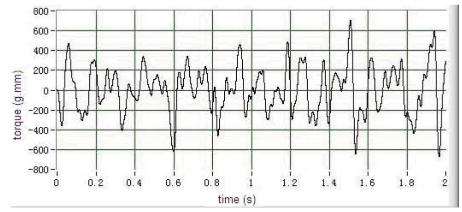
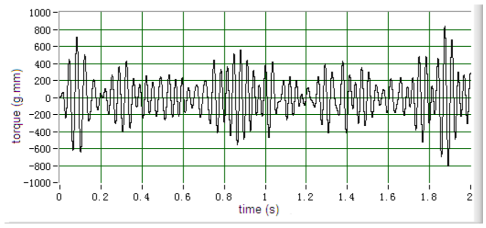


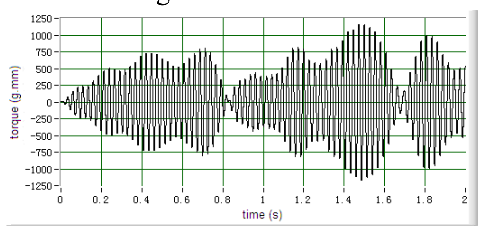
Fig.5 The relation of rotational Speed and friction moment



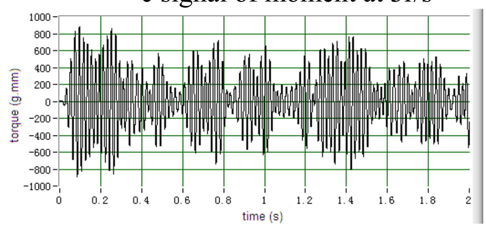
a signal of moment at 1r/s



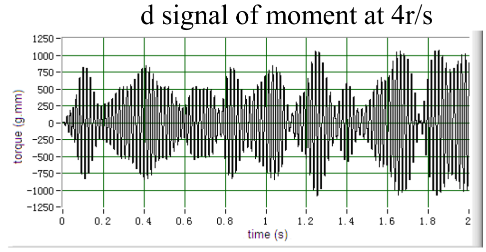
b signal of moment at 2r/s



c signal of moment at 3r/s



d signal of moment at 4r/s



e signal of moment at 5r/s

Fig.6 Filtered signal of friction momentt different rotational speed

The friction resistance condition of ball crew pair of inner loop is different from that of outer loop and the resistance force of ball is far small than that of outer loop when the ball moving in reverser. So the friction of ball when it climbs over the top of reverser can be ignored. The friction moment of screw in both directions is roughly same.

3.2 The variation of fluctuation of friction moment under the action of axial force

Generally, the resistance of ball when it moves on the race is different under the action of different axial force. Therefore, the friction moment varied with the variation of axial force. But there exist large difference between ball screw of inner loop and that of outer loop.

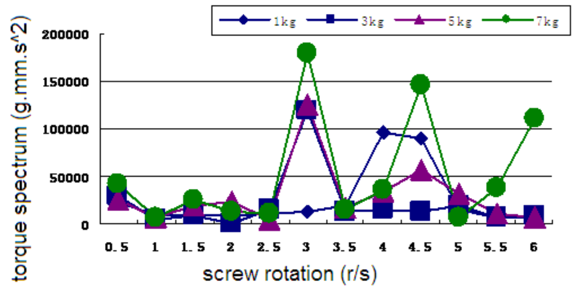


Fig.7 The relation curve of screw's rotational speed and the fluctuation of friction moment

Because lots of factors affect the value of friction moment of screw and tests' data include many complex parameters, the influence of ball's movement on friction moment was mainly analyzed. The original signal was filtered in order to get the relation of rotational speed and the fluctuation of moment. Figure 7 shows the processed signal.

Figure.6 shows the amplitude of frequency of processed friction moment's signal. There is no obvious corresponding relationship between screw's rotational speed and friction moment's fluctuation. The friction moment of screw changes not obviously with the increase of speed.

Friction moment fluctuate not obviously under the action of small axial force while obviously at some speed under the action of large axial force.

Friction moment fluctuate drastically at the speed of 3 r/s, 4.5r/s under the action of axial force of 3kg, 5kg and 7kg.

According to figure 7, although friction moment has the certain fluctuation at the certain speed, the overall fluctuation is small as the axial force changes. Comparing with ball screw of outer circulation in reference 1, friction moment fluctuate drastically at low speed and not drastically with the increase of speed, but it nearly keep unchanged in the case of inner circulation and nearly has nothing to do with the speed. Similarly, the axial force has small influence on friction moment's fluctuation in the case of ball screw of inner circulation.

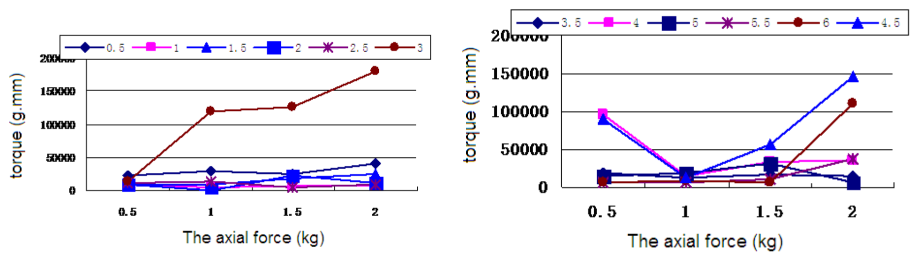


Fig.8 The relation curve of axial load and the fluctuation of friction moment

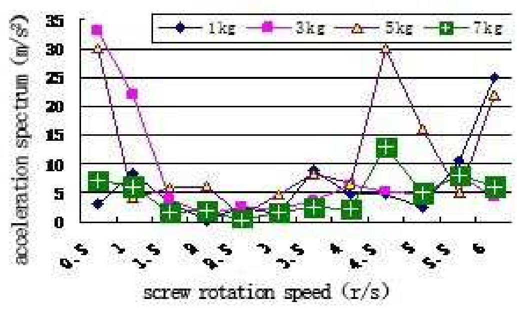


Fig.9 The relation curve of rotational speed and ball's impact

Besides, figure 8 shows the changing curve of fluctuation of the friction moment at different rotational speed and under the action of different axial force. The fluctuation of the friction moment is obvious at the speed of 0.5kg but not obvious at speeds of others. Axial force has greater influence on screw's friction moment when screw rotates at small speed. That conforms to the movement characteristics of ball when it moves from one race to other race.

3.3 The relationship of speed and the ball impact under the axial force

There is a greater change in balls' direction of motion when they change their direction on the rollaway nest, which inevitably lead impact between the inverter and the screw ball, and its change has a connection with the fluctuation of friction torque.

As the ball screw structure is complex, each parameter changes will affect the impact properties of the screw, the impact of the ball on the screw is only considered here when it goes in and out the rollaway nest of inverter.

Figure 9 shows that the ball's impact is large when the screw speed is low. It is visible that the effect of ball impact is obvious during changing its direction when speed of the ball is low; when the ball speed is greater than 1.5r/s, the effect of its impact becomes small; and at other speed, the impact has a fluctuation, but is relatively stable on the whole. For a word, for the ball screw of the inner circulation, the impact of the ball on the screw is small when he balls change their direction, so the system runs relatively stably.

4 Conclusion

Test results show that, under the effect of axial load, the whole friction torque of screw is increasing with the increase of screw speed. Meanwhile, the friction engendered when the ball scrambles over rollaway nest is same, so the forward and inverse friction moment of the ball screw is roughly the same.

For the two types of circulation (inner circulation and outer circulation), the ball friction is roughly different. According to the analysis, the friction loss is small when the balls change their direction on raceway under inner circulation, thus the friction torque fluctuation is relatively small; and for the inner circulation type ball screw, the speed has a small influence on the friction torque fluctuation. Simultaneously, the axial force has also a small influence on the friction fluctuation under the internal circulation type ball screw.

For the inner circulation type ball screw, the vibration impact is smooth under the speed except at some low speed, and the axial force has a small influence on the impact of inner circulation type ball screw.

From the analysis above, the friction torque fluctuation and impact of inner circulation type are smaller than the counterparts of outer circulation. Notably, it’s different from the inner circulation type ball screw, the outer circulation type ball screw owns more load laps, so it can bear more load. The result has a good reference value for ball screw design and theoretical calculations at the low-speed running state.

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