Motion Characteristics Analysis of Circulating Roller Screw Pair

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Abstract. With the increasing demand for large thrust and small volume mechanism that converts rotary motion into linear motion, the application of roller screw pair has gradually increased. In order to study the characteristics of the circulating roller screw pair, and solve the common problems in engineering design and manufacturing, this paper has conducted theoretical analysis and research on the working principle, motion characteristics and geometric relations of the circular roller screw. The equation of the motion relationship of the circulating roller screw is derived, and the relationship between the lead formulae and the structural parameters of the cyclic roller screw is given.

1. Introduction
The planetary roller screw pair is a mechanism that converts rotary motion into linear motion. The rolling element between the nut and the screw is a threaded roller, the roller rotates along the screw thread track and revolves around the screw, while driving the nut to reciprocate linearly. Numerous contact lines can make the planetary roller screw pair have a very strong carrying capacity. With the development of industrial robots, aerospace, and weapon systems, the demand for large-thrust, small-volume rotary motion to linear motion components continues to increase, and the advantages of planetary roller screw pairs are increasingly prominent. Domestic research on planetary roller screw pairs has also gradually increased. Jin Qianzhong et al. [1] analyzed and studied the operating characteristics, working principles and geometric relationships of planetary roller screws. Chen Manlong [2] analyzed the working principle of the roller screw pair and gave the calculation method of selecting the roller screw pair. Zhao Ying et al. [3] studied the meshing relationship between the screw and the roller by establishing the screw thread curved surface and roller curved surface equations, thus providing a theoretical basis for the selection of mechanism parameters. Wei Zhenxing et al. [4] analyzed and optimized the structural parameters of the planetary gear in the planetary roller screw. Comelius et al. [5] introduced a higher efficiency roller screw system from the structure, namely the circulating ball screw pair. It can be seen that there are many types of roller screws, and at present domestic scholars have done a lot of research on the working principle and parameter calculation of planetary roller screw pairs, but most of them are carried out for standard roller screw pairs. There are relatively few calculation studies on circulating planetary roller screw pairs. In this paper, the working principle, motion characteristics and geometric relationship of the roller-circulating roller screw pair are analyzed in detail in accordance with the difference between the roller-circulating roller and the roller non-circulating roller. Finally, the relationship between the lead calculation formula and the structural parameters is obtained.
2. Classification of planetary roller screws:
Planetary roller screws are mainly divided into two categories in Figure 1: roller non-circulating type (RGTB series and RGTI series) and roller circulating type (RGTR series) (see Figure 1).

Roller non-circulating RGTB series roller screw, the main screw is a multi-head screw (mostly have 5 screws), the thread tooth shape is triangular, the nut is internal thread, the tooth shape is the same as the main screw, the roller is single head thread, and the tooth shape is the same as the main screw. In this way, there is no axial displacement between the nut and the roller, the movement principle of the roller non-circulating RGTI series planetary roller screw is basically the same as the RGTB series except that the nut system is reversed. Roller non-circulating roller screw pair due to the screw and nut must be multiple heads, the pitch is small when the lead is small (the pitch is the lead divided by the number of heads), the tooth depth is shallow (the tooth depth is less than half of the tooth pitch), making processing difficult, and the lead is generally greater than 5mm.

The screw and nut of the recirculating roller screw pair are the same as the standard planetary roller screw, the tooth angles are both 90°. The screw and nut thread can be selected from single or multiple heads. Planetary rollers no longer use single head threads instead of a ring groove without a helix angle, there is no ring gear at both ends of the nut, but a special-shaped reset cam. The function is to return to the initial position of the bottom end of the nut thread after the roller makes one rotation along the nut thread, and re-engage with the screw thread, the function of the ball return device similar to the ball screw. The nut is machined with a groove in the radial direction, so that when the roller enters the cycle, it can be pushed away from the screw thread by the cam and return to the initial engagement position in the axial direction. This change makes it possible to design and process the planetary roller screw with a smaller lead.

3. Working principle and motion characteristics of circulating roller screw pair
The circulating planetary roller screw pair is driven by the screw, the nut is fixed in the circumferential direction, and is composed of the main screw, the nut, the roller and the cage. The nut and the screw are processed with a single head or multi-start thread with a tooth angle of 90°, internal nut thread and external screw thread are respectively engaged with the roller, the roller is machined with a 90° annular groove perpendicular to the axis, the helix angle is 0; the roller is installed in the roller table to ensure the rollers distance cage. The nut is radially machined with grooves parallel to the roller axis for the roller to circulate, and there are two cam blocks on the end face of the nut that push the roller back to the initial position. Multiple rollers are installed in the cage and are equally spaced along the circumferential direction. The roller spins along the screw thread track and revolves around the screw,
At the same time, the screw ascends along the axis direction of the main screw, drives the nut to perform linear reciprocating motion and spirally along the axis direction of the nut, after one revolution along the nut, under the action of the cam block, it returns to the initial position along the groove in the nut. The roller table in the cage ensures the distance between the rollers and eliminates the inclination moment of the rollers caused by the inconsistency between the helix angle of the nut and the helix angle of the screw.

The screw rotates and the nut does not rotate. The screw and the nut have the same thread rotation, and the roller is an annular groove. As shown in Figure 1, Figure 2, and Figure 3, \( d_r \), \( d_n \), and \( d_s \) represent the diameter of the roller, nut, and the contact point diameter of screw, \( d_m \) is the diameter of the roller revolution; \( \omega' \) is the angular velocity of the roller revolution, \( \omega_n \) is the angular velocity of the screw, \( s \) is the pitch between the nut and the screw (roller is the groove spacing), \( n_n \) is the number of nut heads, \( n_s \) is the number of screw heads.

To meet the needs of the assembly relationship:

a. The transmission pitch circle diameter of nut, roller and screw meets the relationship
   \[ d_n = d_s + 2d_r \]  

b. The pitch of the nut and the lead screw is equal to the pitch of the ring groove of the roller.

c. The number of rollers: According to the revolution diameter of the rollers \( d_m = d_s + d_r \), the maximum number of rollers is less than or equal to \( \frac{\pi d_m}{d_r} \).

To meet the transmission relationship:

a. The axial length of the groove on the nut and cage is greater than or equal to the length of the roller plus the lead of the nut.

b. The height of the end cam of the nut is equal to the lead of the nut.

c. The depth of the groove in the radial direction of the nut is greater than the total height of the teeth of the roller ring groove.

The cam shape and cage structure are shown in Figure 2:

![Figure 2 Structure schematic diagram of the cam and cage](image)

Suppose there is a rolling motion between the roller and the screw and the nut. From the geometric relationship, it can be known that point A is the instantaneous center of circle, and the linear velocity of point B is twice the linear velocity of point C.

At point B, the linear velocity of the roller and the screw is equal, we can get:

\[ \frac{\omega'd_m}{2} = \frac{\omega d_s}{4} \]  

(2)
According to the principle of planetary transmission, a reverse revolution angular velocity is added to all components on the nut-reversed planetary roller screw pair to convert the epicyclic gear system into a fixed-shaft gear system. Then formula (3), formula (4) and formula (5) are established:

\[
\frac{\omega_n - \omega'}{\omega_n - \omega'} = \frac{d_r}{d_n} \tag{3}
\]

\[
\frac{\omega_s - \omega'}{\omega_s - \omega'} = \frac{d_s}{d_s} \tag{4}
\]

\[
\frac{\omega_n - \omega'}{\omega_n - \omega'} = \frac{d_s}{d_n} \tag{5}
\]

The above formula can be obtained by:

\[
\omega' = \frac{\omega}{2} \cdot \frac{d_s}{d_m} = \frac{\omega}{2} \cdot \frac{d_s}{d_s + d_r} \tag{6}
\]

\[
\omega_\mu = \frac{\omega}{2} \cdot \frac{d_s}{d_n} \cdot \frac{d_s + 2d_r}{d_s + d_r} \tag{7}
\]

When the screw rotates one revolution, the axial displacement of the roller relative to the nut is the sum of the displacement of the roller's spin-up and the displacement of the roller's revolution along the nut's spiral.

\[
H_1 = \frac{\omega'}{\omega} n_n s + \frac{\omega_\mu}{\omega} s \tag{8}
\]

The meaning of the symbol is that the minus sign indicates that the spiral direction is the same, and the plus sign indicates that the spiral direction is opposite. In engineering, consider reducing the inclination moment of the roller caused by the inconsistency between the helix angle of the nut and the helix angle of the screw, generally in the same direction, then:

\[
H_1 = \frac{\omega'}{\omega} n_n - \frac{\omega_\mu}{\omega} s \tag{9}
\]

Since the roller is an annular groove, the spiral angle is 0, so the axial displacement caused by the roller spin.

\[
\frac{\omega_\mu}{\omega} s = 0 \tag{10}
\]

The axial displacement of the roller relative to the nut is:
When the screw rotates once, the axial displacement of the roller relative to the screw is related to its rotation, revolution, and screw lead.

Therefore:

\[ H_2 = \frac{\omega'}{\omega} n_s s + n_s s \]

Similarly,

\[ H_2 = \frac{\omega'}{\omega} n_s s \pm n_s s \]

Due to \( \frac{\omega'}{\omega} s = 0 \), Then the axial displacement of the roller relative to the lead screw is:

\[ H_2 = \frac{\omega'}{\omega} n_s s + n_s s \]  

The axial displacement of the nut relative to the screw is the axial displacement of the roller relative to the nut minus the axial displacement of the roller relative to the screw, ie:

\[ H_1 - H_2 = \frac{\omega'}{\omega} n_s s - \frac{\omega'}{\omega} n_s s \mp n_s s \]

The lead \( P \) is the axial displacement of the nut relative to the lead screw:

\[ P = H_1 - H_2 = \frac{\omega'}{\omega} n_s s - \frac{\omega'}{\omega} n_s s \mp n_s s \]  

When the number of nut heads is the same as the number of screw heads, when \( n_n = n_s, P = \mp n_s s \). The lead takes a positive value, ie \( P = n_s s \), \( s \) is the pitch.

Because \( \omega' = \frac{\omega}{2} \cdot \frac{d_s}{d_{ns}} = \frac{\omega}{2} \cdot \frac{d_s}{d_s + d_r} \)

When the number of nuts and screw heads are different, the lead of the screw pair is:

\[ P = H_1 - H_2 = \frac{d_s}{2(d_s + d_r)} (n_n - n_s) s \mp n_s s \]  

4. Conclusion

Circulating roller screw pair, the roller is designed as an annular groove, and its spacing is equal to the pitch of the nut and screw thread, The screw and nut can be designed as single-head or multi-head thread. When the number of nuts and screw heads are equal, the lead is \( P = n_s s \), When the number is not equal, the lead is

\[ P = H_1 - H_2 = \frac{d_s}{2(d_s + d_r)} (n_n - n_s) s \mp n_s s \]

In engineering, in order to facilitate processing and lead calculation, and to reduce the tilting moment of the roller, the nut and the screw are generally designed to have the same number of heads and the number of heads is less than or equal to 2.

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