Study on jamming mechanism of the planetary roller screw mechanism

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Abstract. This paper explores if there exists jamming phenomena in the planetary roller screw mechanism. Three kinds of jamming phenomena, such as mechanical jamming, dead point jamming, and self-locking jamming, are elaborated by using static analysis of the planetary roller screw mechanism. The results show that mechanical jamming and dead point jamming won’t happen in the planetary roller screw mechanism under the condition of high strength materials, high post-treatment hardness and without regard to error. And when the nut bears unbalanced loads or when the nut and the roller may self-lock in small pitch, the variation of input torque and output velocity is analysed by dynamics simulations. The fact that the planetary roller screw mechanism will not be self-locking jamming is verified.

1. Introduction

Planetary roller screw mechanism (PRSM) is a mechanical transmission device by helical surface meshing of components for converting rotary motion into linear motion [1]. The PRSM has the advantages of heavy loads, high precision, and long life [2], and has been widely applied to the electromechanical actuators (EMAs) to realize the electric drive of mechanical equipment [3], such as aerospace, weapons and equipment, medical equipment, precision machine tools and robots [4].

Generally, the PRSM has only single redundancy in EMAs. Therefore, the reliability of the PRSM is very important, which directly determines the safety of EMAs. Similar to ball screw mechanism (BSM), many failure modes may also exist in PRSM. Especially, the jamming phenomenon is one of the most common failure modes concerned in the application of flight redundant control systems.

In the research of EMAs jamming fault, Zhu et al. [5] evaluated the reliability of actuation system architecture and the failure probability of different actuation, with or without considering jamming. Ismail et al. [6] developed a hybrid vibration-based detection technique for some of the mechanical faults of flight control electro-mechanical actuators, namely partial jam and ball screw spalling. In the study on jamming mechanism of helical transmission, Yang [7] explained the BSM in the pitch and rolling transmission device of sea radar was jammed. Chen [8] revealed the mechanism of jammed BSM through theoretical analysis. Gong et al. [9] elaborated the causes of ball slipping and self-locking effect in the BSM as well as the influence on the high-speed performance. Xu et al. [10] described three failure modes of the BSM, including the top fracture of the raceway surface with severe plastic flow and the ball jamming.

For the PRSM, there has been little fundamental research on jamming mechanism to support its engineering application. Therefore, this paper will take PRSM as the research object to explore if there
may exist jamming. First, the definition of jamming in the PRSM is simply described. Next, the mechanical jamming is studied from the point of view of structural characteristics, and self-locking jamming and dead point jamming are further analysed based on static analysis and dynamic simulation under different load conditions. The results provided by this paper are expected to be a basic resource for further PRSM research related to parameter design, fault diagnosis, health management, etc.

2. Definition of jamming mechanism

As shown in Figure 1, the principal components of the PRSM are a screw shaft, nut and equally spaced rollers. The jamming phenomenon is defined as an arbitrary component in the PRSM appears relative stationary during operation. No matter how much driving torque cannot make the roller and nut to produce relative motion. And the PRSM may be jamming due to various errors in theoretical design, manufacturing and assembly process. Therefore, in order to study the jamming phenomenon of PRSM, it will be analysed from the jamming mechanism and the PRSM kinematics point of view. According to the different jamming mechanism of the PRSM, it can be divided into mechanical jamming, self-locking jamming and dead point jamming.

3. Analysis of jamming mechanism

3.1 Possibility analysis of mechanical jamming

Mechanical jamming refers that the relative motion between the screw, the roller and the nut are prevented by surface appearance or particles, such as loose iron chips. Firstly, the entire PRSM is wrapped in its internal shell, and both ends are sealed with a seal ring, so the larger particles of the outside will not enter into the PRSM, isolated from the outside environment. Secondly, during the PRSM operation, iron chips were doped due to wear and fatigue during the PRSM operation, which may disrupt the normal operation of the roller, the screw and the nut. However, these iron chips are generally smaller in size and can be mixed in the middle of the grease, so they will not cause components jamming. Thirdly, the continuous screw raceways, nut raceways and rollers raceways are not only smooth but also of high hardness, which will not cause large burr or generate plastic concave to jam the PRSM. In fact, through the observation of the raceway, as show in Figure 2, no obvious scratch marks were found in the surface of the screw raceway. Moreover, the machining of the PRSM generally adopts CNC machine tool, with high precision, and it is impossible to cause mechanical jamming due to the surface appearance. Therefore, in the sealed performance of the shell and the use of high strength materials and high post-treatment hardness, the PRSM generally does not appear mechanical jamming.

3.2 Possibility analysis of dead point jamming

Dead point jamming refers to the normal operation of the mechanism due to the dead point position. The PRSM forces diagram is shown in Figure 3. Where, $F_{sr}$, $F_{nr}$ represent the supporting force of the screw and nut on the roller, $F_{t1}$, $F_{t2}$, $F_{o1}$, $F_{o2}$, $F_{0o}$ represent the radial force, the axial force, the axial force of the screw and nut on the roller, and $F_{f1}, F_{f2}$ represent the friction force of the screw and nut on the roller.

According to Figure 4, the contact force between the screw and the roller can be obtained by
where \( \alpha \) is the helix angle of the screw, \( \beta \) is the flank angle of the screw section, and \( \mu \) is the friction coefficient.

The friction between the screw and the roller is

\[
F_f = \mu F_w
\]

According to formula (1) and formula (2), the axial force of the screw on the roller can be expressed as

\[
F_{nl} = \frac{F_w \cos \alpha \tan \beta}{\sqrt{(1 + \cos^2 \alpha \tan^2 \beta)^2}}
\]

(3)

The component force of friction in the circumferential direction is

\[
F_f = \mu F_w \cos \alpha
\]

(4)

The flank angle of the PRSM is 45° commonly, so

\[
\frac{\sqrt{2}}{2} F_w \cos \alpha < F_{nl} < F_w \cos \alpha
\]

(5)

3.3 Possibility analysis of self-locking jamming

Mechanical self-locking refers to the phenomenon that no matter how to increase the driving force cannot make the machine move, which is static in the initial state[8]. For the PRSM, when the moment that is composed of the normal force of the roller given by the nut and that of the roller given by the screw is less than or equal to the friction torque caused by friction between them, the roller will lock itself and PRSM will be jammed.

3.3.1 Possibility analysis of self-locking jamming without regard to error. Because the helix angle of the roller is different from that of the screw, this will cause the position of the meshing point of the roller and the screw not at the middle diameter of them. Unfolding along the spiral curve at the point of engagement, simplifying the roller to a sphere, as shown in Figure 4, where \( F_{nr} \) is the normal force of

![Figure 2. Worn screw](image)

![Figure 3. Force analysis diagram of roller.](image)
the screw on the roller, \( F_f \) is the friction force, \( \alpha \) is the helix angle of the screw, \( \beta \) is the flank angle in the screw section, and \( F \) is the driving force acting in the screw.

During the PRSM movement, the screw is always used as the driving part and the roller as the driven link. The driving force acts on the screw, the self-locking condition is not satisfied. Therefore, there is no self-locking relationship between the screw and the roller.

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\[
f \geq \tan \beta'
\]

where \( f \) is the friction coefficient, \( \beta' \) is the equivalent helix angle.

Combined with Figure 6, we can get

\[
\tan \beta' = \frac{b}{\sqrt{(a \tan \beta)^2 + b^2}} + a
\]

where \( a \) represents the distance between the meshing point and the tooth root, \( b \) represents the distance between the rollers in the circular direction, \( \alpha_n \) represents the helix angle of the nut, and \( \beta \) represents the flank angle of the screw in the section.

Substituting \( b = \frac{\pi d}{n} \), \( \beta = 45^\circ \) into formula (6), the formula (5) can be rewritten as
\[ f \geq \frac{\pi d_r}{n \tan \alpha} + a \left( a^2 + \frac{\pi d_r}{n} \right)^{\frac{1}{2}} \]  

In summary, the screw and the roller won’t occur self-locking, while the roller and the nut may occur self-locking in the case of small pitch. But the roller will still slide relatively to the screw and the PRSM won’t happen self-locking jamming without regard to error.

### 3.3.2 Possibility analysis of self-locking jamming under the condition of unbalanced load.

The load of PRSM is different in different working process and possibly changes as time goes on. In general working conditions, the nut only bears the axial load, but in the case of lifting device, aircraft rudder surface, PRSM also bears unbalanced load because of the changing external load. Therefore, the possibility of PRSM jamming will need to be analysed in the following elaboration considering the normal load and off-load. As shown in Figure 6, the PRSM is subjected to axial load and radial load, which can be equivalent to that the nut is subjected to axial load, radial load and bending moment.

![Figure 6. PRSM force analysis diagram under the condition of unbalanced load.](image)

![Figure 7. Schematic diagram of PRSM under bending moment.](image)

![Figure 8. Dynamic model of PRSM.](image)

Figure 7 shows that PRSM is under bending moment. Although the PRSM bears bending moment, radial force and axial force, those can be balanced by the gear meshing between the end gear of the roller and the annular gear, the torque produced by the contact force of roller and screw, and the torque at the supporting bearing. This only makes the contact force between the roller and the nut increases, so as to increase the friction, increase the wear and tear. Even so, PRSM will still work properly.

### 4. Simulation analysis and discussion

In this paper, the dynamic simulation analysis of PRSM using ADAMS software was carried out on the condition that the roller and nut were relatively static due to self-locking phenomenon, internal abrasive particles, too little grease and other reasons, and when the nut was under unbalanced load. The PRSM structural parameters are shown in Table 1.
Table 1. PRSM structural parameters.

| Parameters       | Symbol | Screw | Roller | Nut |
|------------------|--------|-------|--------|-----|
| Equivalent radius| r/mm   | 15    | 5      | 25  |
| Lead             | l/mm   | 10    | 2      | 10  |
| Number of threads| n_i   | 5     | 1      | 5   |
| Helix angle      | λ_i/°  | 6.05666 | 3.6426 | 3.6426 |
| Pitch            | p_i/mm | 2     | 2      | 2   |
| Flank angle      | β_i/°  | 45    | 45     | 5   |
| Roller contour radius | r_Re/mm | -     | 7.07   | -   |

In SOLIDWORKS software, PRSM model is built according to its parameters, and imported into ADAMS software. Subsequently, PRSM dynamic model as shown in Figure 8 can be obtained. This article uses the Impact Function method for calculating the contact force among them. The parameters of contact force are set in the simulation analysis as follows. And it sets stiffness coefficient as $K=1\times10^5\text{N/mm}$, force exponent as $e=1.5$, damping as $C=50\text{N s/mm}$, penetration depth as $d=0.01\text{mm}$. In order to make the simulation effect more consistent with the reality, the influence of friction is considered when adding contact force. Coulomb method was used to calculate the friction, where the parameter was that static coefficient was set as $\mu_s=0.23$, dynamic coefficient was set as $\mu_d=0.16$, stiction transition was set as $v_s=100\text{mm/s}$, and friction transition was set as $v_d=1000\text{mm/s}$.

Table 2. PRSM operating condition.

| Operating condition one | Operating condition two | Operating condition three |
|-------------------------|-------------------------|--------------------------|
| Normal condition        | Axial load 200N         | Axial load 600N          |
| The roller and nut are relatively static | Axial load 200N | Axial load 600N | Axial load 1000N |
| The nut bears unbalanced load | Axial load 1000N | Axial load 1000N | Axial load 1000N |
| Bending moment 30Nm     | Bending moment 90Nm     | Bending moment 150Nm     |

Figure 9. The screw torque curve under operating condition one (a) normal condition (b) the roller and nut are relatively static (c) the nut bears unbalanced load.

In order to explore the torque change of PRSM when the roller and nut are relatively static, where pure sliding friction is between the roller and the screw, and PRSM under partial load, this paper carried out multiple sets of simulation analysis on PRSM, in which the speed of the screw is always 10r/s, and the remaining parameters are shown in Table 2. Set the simulation time to 0.4s and the simulation step size to 0.001s.
Figure 10. The nut speed curve under operating condition one (a) normal condition (b) the roller and nut are relatively static (c) the nut bears unbalanced load.

Figure 11. The screw torque curve under different operating conditions (a) operating condition one (b) operating condition two (c) operating condition three.

The simulation results of the PRSM under operating condition one are shown in Figure 9, 10, and 11 respectively. It can be seen from Figure 9 that the average of the screw torque under normal condition is 1344.987Nmm, that under the roller and nut are relatively static is 824.861Nmm, that under the nut bears unbalanced load is 4587.211Nmm. By comparing Figure 9 (a), (b), and (c), the torque of the screw is related to the axial load. Figure 10 shows the nut speed curve under operating condition one, it is obvious that the nut speed is 100rpm and is in accord with the theory. From Figure 11 (a) and (b) it can be seen that the axial load is proportional to the input torque of the PRSM, and screw torque is increasing correspondingly as the axial force, it can be seen from (c) that radial force and bending moment has no impact on the screw torque. And it is mainly because the PRSM is pure of rigid body, without considering the deformation, so the bending moment and axial force impact on the movement.
To sum up, PRSM does not get jamming when the roller and nut are relatively static and under partial load, and only the axial force has an effect on the torque of screw the contact force of roller.

5. Conclusions
In this paper, the question if the PRSM will be jammed was discussed by using static analysis. The results show that three kinds of jamming phenomena, which are mechanical jamming, dead point jamming and self-locking jamming, won’t occur in the PRSM under the condition of high strength materials, high post-treatment hardness and without regard to error. However, under the condition where formula (7) is satisfied, the roller and nut may be self-locked, and it indicates the roller and nut are relatively static. The simulation analysis is used when roller and nut are relatively static and when the PRSM is under the condition of unbalanced load, and the result proves PRSM will not be jammed.

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