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# Experiment Analysis of the Correlation Between Lubrication and Friction Torque in a Ball Screw

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ABSTRACT: At first, based on Dowson's thinness film thickness formula and the friction torque formula, established a single roller theory model of thinness oil film thickness and friction force in theory. Then to put forward a hypothesis about the relationship between the lubricating grease amount and the friction torque of ball screws. At last, carry out the experimental study of lubrication and friction torque under the above assumptions. The experiment's results verified the hypothesis and showed that, with the increasing amount of the lubricating grease, the friction torque of the ball screw had a sharp decrease at first, then remained unchanged, and finally had a slight increase. It can be concluded from the variation of the friction torque that the lubricating amount corresponding to the unchanged region of the friction torque is the optimal quantity of the lubricating grease.

Index Terms: Ball screws, Friction torque, Lubrication, Amount of the lubricating grease.

## 1 INTRODUCTIONS

The friction torque is a kind of resistance torque in ball screws that consists of various friction factors, which is one of the most important performance parameters and reflects the friction characteristic of the mechanism [1]. Friction torque leads to energy loss that decreases transmission efficiency [2-3]. Also, temperature increases caused by friction torque have negative influences on positioning accuracy. The friction torque of a ball screw is a comprehensive mechanical index that reflects the processing quality and performance of the ball screw [4]. Lubrication is necessary because it ensure the operation of ball screws. It plays an important role in improving transmission accuracy and the service life of ball screws. There are various factors that can affect the frictional torque in ball screws. One of the factors is the quantity of lubricant. It causes fluctuations in frictional torque, which have a negative influence on the fluency and stability of ball screw motion. Thus, studying the mechanism of friction torque fluctuation with different quantities of lubricant and analyzing the reasons for it are necessary because this research can improve the quality of ball screws and the dynamic performance of NC machine tools. The friction torque changing will make the ball screws operation uncomfortable and affect the positional accuracy. Olaru el.[5]reported one kind of model to estimate the friction torque of the ball screws which only estimate the average value. This model did not indicate the variation of the friction torque during the operational of the ball screws. Zhang el.[6] reported that the friction torque of the ball screws changed differently by using the various kinds of lubricant grease. But few papers indicate the relationship between lubrication grease quantity and the friction torque which is verified by testing bench. In this paper, the variation of frictional torque under different quantities of lubricant and the reason are analyzed, and the optimal lubricant quantity is identified based on the analysis of friction torque and the lubrication conditions.

## 2 THEORETICAL ANALYSIS OF BALL SCREW FRICTIONAL FORCE

### 2.1 *Composition of the ball screw frictional torque*

According to the generation mechanism, the friction torque of a ball screw is mainly the result of friction between the balls and the screw raceway as well as the nut raceway (including elastic hysteresis, differential sliding and revolving sliding). The sliding friction between balls, the friction between balls in the return tube (including the impact caused by balls in and out of the return tube and friction between balls and the return tube raceway) and the viscosity resistance of lubricant[7].

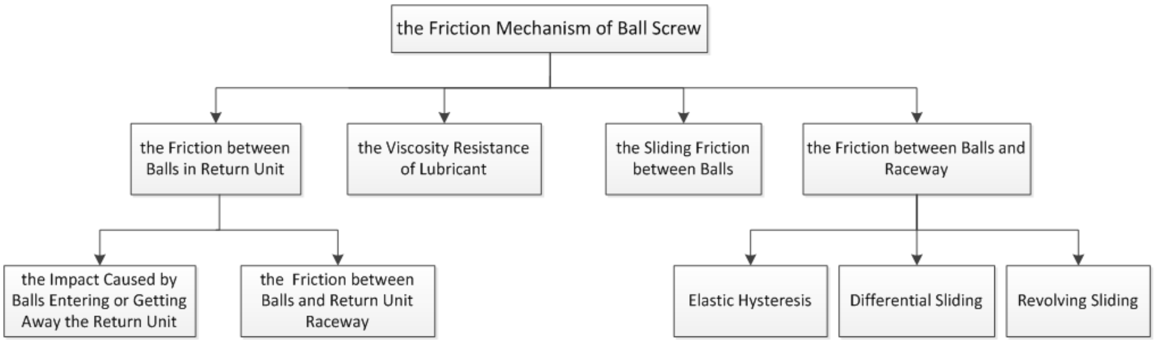



Figure 1. Constitution of the friction mechanism of ball screw.

## 2.2 *Total friction torque of ball screw*

In the operation process of a ball screw, these friction mechanisms all function at the same time, which are coupled. Therefore, simply stacking all the frictional torques caused by different reasons would be unscientific [8]. Multiplying the total frictional force with its force arm can reveal the total frictional torque.

The total friction force of ball screws with lubrication is shown as[9]:

$$F_{X_{\bar{n}}} = \int_{-B_{\bar{n}}}^{B_{\bar{n}}} \int_{-A_{\bar{n}}}^{A_{\bar{n}}} \tau_{X_{\bar{n}} Z_{\bar{n}}} \Big|_{Z_{\bar{n}} = h_{\bar{n}}} d_{i_{\bar{n}}} d_{j_{\bar{n}}} = \int_{-B_{\bar{n}}}^{B_{\bar{n}}} \int_{-A_{\bar{n}}}^{A_{\bar{n}}} \left( \frac{\partial \overline{P}_{\bar{n}}}{\partial i_{\bar{n}}} \frac{h_{\bar{n}}}{2} + \frac{\eta_{v_{\bar{n}}} (u_2 - u_1)}{h_{\bar{n}}} \right) d_{i_{\bar{n}}} d_{j_{\bar{n}}}$$

$$(\bar{n} = i_L, i_R, o_L, o_R) \tag{1A}$$

$$F_{Y_{\bar{n}}} = \int_{-B_{\bar{n}}}^{B_{\bar{n}}} \int_{-A_{\bar{n}}}^{A_{\bar{n}}} \tau_{Y_{\bar{n}} Z_{\bar{n}}} \Big|_{Z_{\bar{n}} = h_{\bar{n}}} d_{i_{\bar{n}}} d_{j_{\bar{n}}} = \int_{-B_{\bar{n}}}^{B_{\bar{n}}} \int_{-A_{\bar{n}}}^{A_{\bar{n}}} \left( \frac{\partial \overline{P}_{\bar{n}}}{\partial j_{\bar{n}}} \frac{h_{\bar{n}}}{2} + \frac{\eta_{v_{\bar{n}}} (v_2 - v_1)}{h_{\bar{n}}} \right) d_{i_{\bar{n}}} d_{j_{\bar{n}}}$$

$$(\bar{n} = i_L, i_R, o_L, o_R) \tag{1B}$$

Where $\tau_{X_{\bar{n}} Z_{\bar{n}}}$ and $\tau_{Y_{\bar{n}} Z_{\bar{n}}}$ denote the frictional shear stresses in the $X_{\bar{n}} - Y_{\bar{n}}$ and $Y_{\bar{n}} - Z_{\bar{n}}$ planes, respectively. $i_{\bar{n}}$ and $j_{\bar{n}}$ are coordinates of an arbitrary point at the $X_{\bar{n}} - Y_{\bar{n}}$ plane. $\overline{P}_{\bar{n}}$ is the distribution of hydrodynamic pressure formed at the contact area. $h_{\bar{n}}$ denotes the oil film thickness at the contact area. $\eta_{v_{\bar{n}}}$ denotes the lubricant viscosity. $A_{\bar{n}}$ and $B_{\bar{n}}$ denote the half lengths of the long and short axes of the contact area, respectively. $u_2$ and $u_1$ denote the linear velocities in the $X_{\bar{n}}$ direction, respectively. $v_2$ and $v_1$ denote the linear velocities in the $Y_{\bar{n}}$ direction, respectively. As shown in the formula, friction force and oil film thickness are related. That is, frictional torque and oil film thickness are related.

## 2.3 *Drag torque of the lubricant viscous force*

The viscous force of lubricant can also produce frictional torque itself, which may hinder the rotation of ball screws. Due to the friction between the fluid's internal molecules and the adhesion force between the fluid and solid surfaces, shear deformation will be caused when the lubricant flows[10]. The fluid viscosity influences its ability to resist shear deformation. In the structuring principle, a ball screw is similar to a bearing. In the analysis of bearing friction, the viscous force of lubricant occupies an important proportion. By imitating the analysis mode for bearings and referring to the results from Pdmgmn's[11] bearing frictional torque experiment, the frictional torque caused by the viscous force of lubricant MR was proposed.

$$M_R = 10^{-7} f_0 (vn)^{\frac{2}{3}} d^3 \tag{2}$$

Where $f_0$ denotes a coefficient that is related to bearing type and lubrication mode; v denotes the lubricant kinematic viscosity, whose unit is $mm^2/s$, and d donates nominal diameter.

# 3 ANALYSIS OF OPTIMAL LUBRICANT AMOUNT FOR BALL SCREWS

Lubrication is indispensable because ball screws are the most easily abraded part of any CNC. However, too much lubricant can cause energy loss, which then turns into thermal energy and influences friction torque. Another damage caused by the excess lubricant is environmental pollution.

If the quantity of lubricant can be reduced, the efficient use of lubricant will be relatively raised. There exists an optimal lubricant amount that will ensure that 100% of the lubricant is utilized in ball screws with no wasted.

In a ball screw operation process, there are three lubrication conditions between the balls and the raceway: boundary lubrication, partial elastohydrodynamic lubrication and complete film elastic flow lubrication. Usually, the film thickness ratio λ is used to distinguish lubrication conditions[12].

$$\Lambda = \frac{h_{\min}}{\sqrt{\sigma_1^2 + \sigma_2^2}} \tag{3}$$

Where $h_{min}$ denotes the minimum film thickness at the contact surface and $\sigma_1$ and $\sigma_2$ denote the surface profile RMS deviation of contact pair. When $\lambda<1$, it is in a boundary-lubrication state. When $1<\lambda<3$, it is in a partial-EHL state. When $\lambda>3$, it is in a complete-film-elastic-flow-lubrication state. Because of the small value of friction torque, the life of ball screw will be great lengthened if it can operate in a good lubrication condition. To understanding the performance of bearings and ensuring the reliable operation of ball screws, the minimum film thickness must be calculated under actual working conditions.

In a ball screw, the contact type between the balls and the raceway is point-to-point and the lubrication problem is a typical elastohydrodynamic lubrication problem. According to the kinematics analysis of ball screws, the short axis of contact ellipse and the entrainment velocity vector, which is related to the contact surface (between balls and raceway) and lubricant, have the same direction. Its minimum film thickness can be calculated using the Hamrock-Dowson formula[12]:

$$H_{\min} = \frac{h_{\min}}{R_x} = 3.63U^{0.68}G^{0.49}W^{-0.073}\left(1-e^{-0.68k}\right) \tag{4}$$

According to Eq.4, the calculation formula for single rolling element mass flow can be obtained using the following equation:

$$q_i = 3.63U^{0.68}G^{0.49}W^{-0.073}\left(1-e^{-0.68k}\right)R_x \tag{5}$$

where $H_{\min}$ is the dimensionless oil film thickness; $h_{\min}$ is the oil film thickness; $R_x$ is the curvature radius sum; and U is the dimensionless velocity parameter, which is stated as

$$U = \frac{\eta_0 u}{E' R_x} \tag{6}$$

where $\eta_0$ is the viscosity of the lubricant oil; $U$ is the average speed of the sliding velocity the components of contact surfaces; E is equivalent elastic modulus; and G is the dimensionless material parameter, which is stated as

$$G = \alpha E' \tag{7}$$

Where α is the viscous pressure coefficient and W is the dimensionless load parameter, which is stated as

$$W = \frac{P}{E' R_x^2} \tag{8}$$

Where P is contact force and k is elliptic parameter; which is stated as

$$k = \frac{a}{b} \tag{9}$$

where a、b is the contact ellipse parameter. Therefore, the minimum demand of lubricating oil, or the best lubricating oil quantity can be expressed as the following:

$$q = \sum_m q_i m \tag{10}$$

Where, m denotes the number of balls.

Using minimum film thickness and lubrication conditions to judge the effect of lubrication is microcosmic. So, the problem is how to judge whether we have the best lubrication effect macroscopically. Under no axial load and no loss of the preloading, a hypothesis is proposed according to above theoretical analysis and the experimental equipment available. Friction torque can be used to judge lubrication effect of a ball screw. With increasing lubricating oil quantities, friction torque decreases at first, then it plateaus at a stable stage, and finally, friction torque increases. The change curve of friction torque seems to be the same as a bathtub.

As shown in Figure.2. Point A represents initial value of the friction torque under no lubricating; point B is turning point at beginning of the stable stage, point B is the best lubrication grease quantity; point C represents the critical value is turning point at beginning of the increasing stage, when the quantity is more than the value of C, the viscous force caused by lubricating grease produces friction torque, which hinders the rotating motion of ball screws. The value of D point is the amount of full of nut space. We divide the change curve into three stages, the first stage of plummeting shows that the friction torque declines with the augment of lubricant amount. The second one is a steady period where the friction torque stays nearly constant. During the third one, the friction torque slows upward trend. Based on the analysis above, the second stage has the beat lubricating oil quantity. Some experiments will be designed to prove our conclusions.

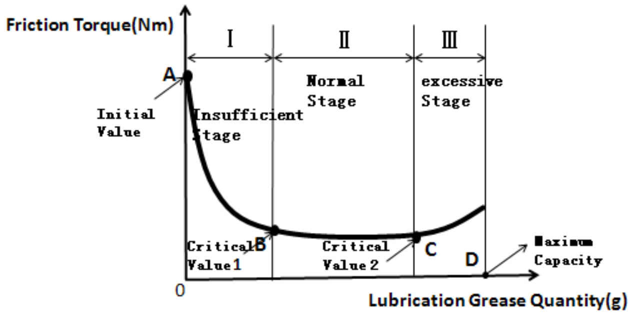
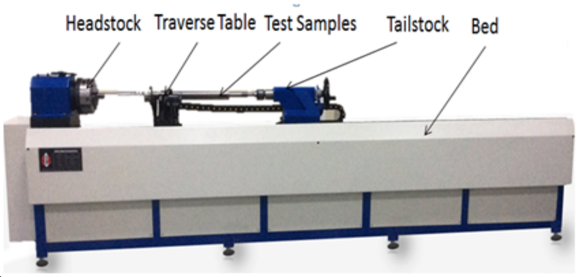



Figure 2. Expect the test results.

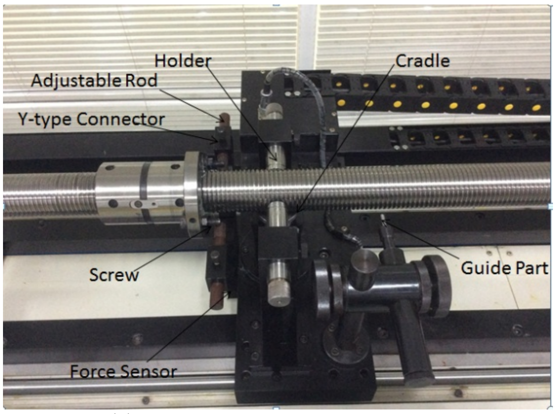
## 4 EXPERIMENT DETAILS

### 4.1 *Introduction to the experimental system for ball screw frictional torque measurement*

The measurement of friction torque was conducted on the friction torque test bench, as shown in Fig.3. The principles of the Friction Torque Measurements: The resistance that limits the nut rotational motion can be measured by a force sensor. Thus, the friction torque of ball screw can be obtained through the sensor. By transforming the value measured by the sensor into digital signals, and multiplying the digital signal and force arm factor, the friction torque of measured ball screw can thus be obtained.




a). Test bench




b). Traverse table

Figure 3. Structure of test bed.

Table 1. Main Technical Parameters of the Friction Torque Measurement.

| Parameters | Magnitude |
|---|---|
| Torque Accuracy | ≤0. 1%F·S |
| Repetitiveness | ≤0. 1% F·S |
| Overload Capacity | 150% F·S |
| Lag | ≤0. 1% F·S |
| Liner | ≤0. 1% F·S |
| Operating Temperature | −20 ～60 □ |

## 4.2 *Experiment of the frictional torque and lubricating grease quantity*

a) The measured ball screw type is HJG-S. Table.2 shows its structure parameters and performance parameters. These kinds of ball screws have high accuracy, small lead deviations and small raceway deviations. Their pre-tightening forces are stable. The diameter of their force arm is 90mm.

Table 2. Structure Parameters and Performance Parameters of Ball Screw.

| Parameters | Magnitude |
|---|---|
| Nominal Diameter/mm | 50 |
| Nominal Lead/mm | 5 |
| Ball Diameter/mm | 3.175 |
| Screw Material | 50GrMo4 |
| Nut Material | 100cr6 |
| Ball Number | 500 |
| Contact Stiffness N/um | 2300N/um |

b) The lubricating grease used was Mobil EP2.

Experimental process:

1) The measured ball screw should be cleaned until it has no oil. To cleaning the oil in the nut, we had to put the ball screw into gasoline, pour gasoline into the ball screw through the nut hole and rotate the nut continuously. Finally, absolute alcohol was used to clean the nut again. Remember that the ball screw must be dry. Starting with no oil was essential for this experiment.

2) The ball screw nut needs to be filled with a certain amount of lubricating grease, as shown in Fig.4.

3) Experiments with different amounts of lubricating grease were conducted under the rotational speeds of 10 rpm, 50 rpm and 90 rpm, respectively. Based on the report, the friction torque maximum value, minimum value, mean value and mean square deviation were obtained.

4) The fitting curve was obtained through multiple measurements.

# 5 EXPERIMENTAL RESULTS

## 5.1 *Effects of the lubricating grease quantity on friction torque*

Friction torques under different lubricating grease quantities were obtained, which can be used to evaluate the lubrication effects. The minimum friction torque value corresponds to the best quantity of lubricating grease.Fig.4 shows the fitting curve on the basis of data. Max/Min curves label the Max/min of the friction torque in experiment which indicates the peak value during the process of testing. Mean Square indicates the stabilization of friction torque. Analysis below is based on the Mean value of the experiment. Two lines (line 1 and line 2) were added in Fig.4 to divide the curves into three areas. Point $B_1$ on Line 1 corresponds to a value of 8.5 g of quantity of lubricating grease, point B is the best lubrication grease quantity; point $C_1$ on line 2 corresponds to a value of 18 g of quantity of lubricating grease is the best quantity of lubricating grease. Besides, the maximum amount of lubricating grease in the nut is 24 g. The changing trend of friction torque with increasing lubricating grease quantities is shaped like a bathtub curve.

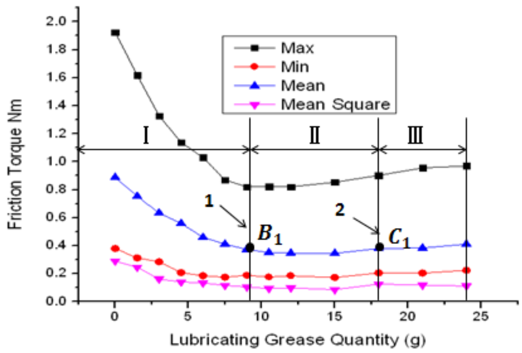



Figure 4. Variation over the friction torque under different quantities of lubricating grease at the rotational speed of 10r/min.

In stage I, the quantity of lubricating grease occupies less than 35% of the space capacity of the nut. Although friction torque values decrease as the quantity of lubricating grease increases, the mean value and mean square deviation are larger. The evaluated lubrication effect is also poor. If a ball screw remains in this stage a long time, its raceway may have abrasions and its positioning accuracy and life may decrease.

In stage II, lubricating grease occupies 35%～75% of the nut space capacity. The mean value and mean square deviation decrease and become stable. The best lubricating grease quantity exists in this stage because of the uniform friction torque wave and reposeful transmission.

In stage III, the quantity of lubricating grease occupies more than 75% of the space capacity of the nut. The mean square deviation is almost invariant due to the reposeful transmission of the ball screw. However, the mean value has a little growth. This phenomenon shows that the viscous force caused by lubricating grease produces friction torque, which hinders the rotating motion of ball screws.

This result also proves that the amount of lubricant has an influence on friction torque. The oil film that exists in friction pairs, which have relative motion, can prevent contact between friction pairs and provide lubricating action as long as the thin oil film has enough carrying capacity and is stable enough.

Obviously, too much or too little lubricating grease reduces the lubrication effect. Too little lubricating grease would have a poor lubrication effect and too much lubricating grease would lead to larger friction torque and environment pollution.

### 5.2 *Effects of the Rotational Speed on Friction Torque*

The friction torque values under the rotational speed of 50 rpm and 90 rpm were measured in the same way. Then the three kinds of the fitting curve were compared, as shown in Fig. 5. The scope of the best quantity of lubricating grease in stage is marked.

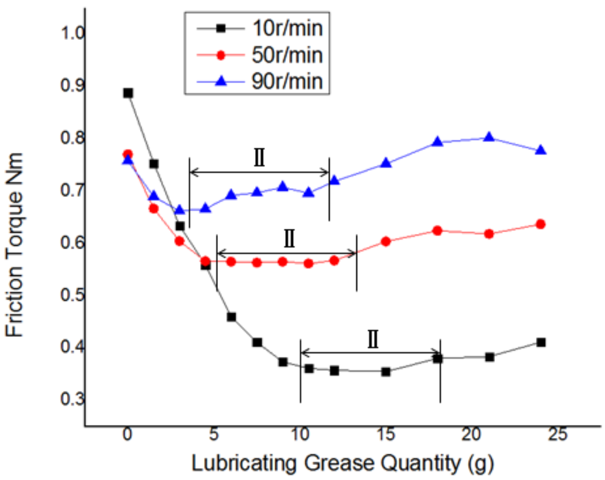



Figure 5. Variation over the friction torque under different quantities of lubricating grease and different revolving speed.

The speed also has an effect on minimal oil film thickness and friction torque. In the condition of insufficient lubrication, the friction torque is small at high speed, which means that the optimal lubrication amount is less. According to equation (5), higher speeds result in thicker thinnest oil film. Besides, according to the Eq. (3), the thicker the minimal oil film thickness the larger the film's ratio, and as a result, the faster and better lubrication state will be reached. Therefore, the grease quantity for the optimal lubrication effect varies with different speeds. As the increasing of the grease, the speed of 90 rpm is apt to reach the optimal lubrication effect compared with that of 10 rpm. However, the friction torque at high speed will rise during the gradual increasing of the grease quantity. According to the viscosity moment formula of the lubricant Eq. (2), the speed is the two-thirds of the viscosity moment, and the viscosity moment will increase as the increasing of the speed. The friction torque at 90 rpm is larger than that at the speed of 10 rpm. This is because the viscous force caused by excessive lubricant hinders the rotation of the screw.

## 6 CONCLUSIONS

1) The influencing factors related to the friction torque of ball screws were analyzed on the basis of the structural characteristics of ball screws and friction force with lubrication. Considering the minimum oil film thickness, the quantity of lubricating grease does have an influence on friction torque.

2) The assumed curve can put forward the qualitative analysis of the best quantity of lubricating grease when the ball screws at the best lubricating effect.

3) The experiments results indicate that, with increased amounts of lubricating grease, the friction torque value is rapidly decreased at first then becomes stable and increased slightly at last. Therefore, the best quantities of lubricating grease can be seen in the stable stage. The experimental results show that rotating speed also affects friction torque.


## ACKNOWLEDGEMENTS

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