The maintenance of ball screw of CNC machine

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Abstract

During the several decades past, Ball screw play an important role in the feed drive system of CNC machines. With the development of manufacturing industry, CNC machine require higher precision delivering motion due to the higher requirement of products quality. Therefore, the reliability and the work performance are crucial standard for ball screw. The wear of ball screw will decrease the preload, which is the mean reason for the failure of ball screw. As the preload can avoid axial backlash and excessive heat generation, So suitable preload can improve the precision and lifecycle of ball screw. Predictive maintenance should be applied to avoid the failure of ball screw. The mean purpose for this paper is to analysis the methods that can monitor the wear of ball screw.

Key words: friction, preload, accutacy, predictive maintenance, current signal, vibration signal

Chapter 1: Introduction

The ball screw is a mechanical linear actuator which can translate the rotation motion to linear motion. Ball screws are widely used in the feed drive system of CNC machine. The main advantages for the ball screw is the high position accuracy at high drive speed. Apart from this, the ball screw also have high mechanical efficiency because of low friction, the efficiency of a typical ball screw can up to 90 percent. The low frication can also increase the lifespan of ball screw, which can reduce the demand for lubrication, parts replacement and also the downtime for maintenance.

However, because of the backlash and friction between the ball-screw and the nut, it's difficult to achieve precise feed drive system. Therefore, we use proper preload to eliminate axial backlash and increase the stiffness of the ball-screw, otherwise the excessive preload will increase the friction. Ball-screw preload also plays an important role in improving the rigidity, noise, accuracy and life of the positioning stage. When the machine start or stop, the acceleration or deceleration of ball-screw will result in the lack of lubrication which can help the heat dissipated and decrease the wear of two contact metal face. So the lack of lubrication will exacerbate the wear and thermal expansion of ball screw. With the increase of the depth of wear, the preload will decrease, which is the main cause of failure for a preloaded ball-screw. Apart from this, the wear can also produce the debris in the ball nut or ball paths preventing free circulation of the ball bearings. The ball bearing may get flats on them due to skidding and spalling, which may in turn damage the ball paths in the screw or the ball nut. Excessive speed is another reason for the failure of ball-screw. The high rotational speeds cause a significant increase in the centrifugal force of the balls and the slip motion formed at the ball and the race way, which decrease the mechanical efficiency. Exceeding the ball nut critical speed can lead to pickup gingers breaking, which allow to the ball bearings to come out of the nut. Exceeding the screw critical speed will cause the screw to whip or vibrate and cause misalignment. The misalignment of ball nut to screw will results in side loading or eccentric loading. It is very important that the ball nut only experiences axial loading. Side loading or eccentric loading may cause the ball bearings to wear flat in places. The bearing may even break out of the return tubes. Many researches also focus on the thermal error. The friction and the bad ability of heat dissipated are the main reason for the thermal expansion, which will reduce the precise of ball-screw and increase the wear. However, the wear induce higher friction, which formed a vicious circle.

Chapter 2: the main problem for the ball screw

2.1 the variations of Friction

2.1.1 the theoretical analysis

The variations of friction including the wear condition, lubrication, manufacturing tolerances, mechanical alignments and heat generated during operations.

1. When the motion of a ball–screw is in the acceleration or the deceleration step, the lubrication condition is usually a mixed or boundary lubrication, and this creates wear at the contact area in a ball–screw.

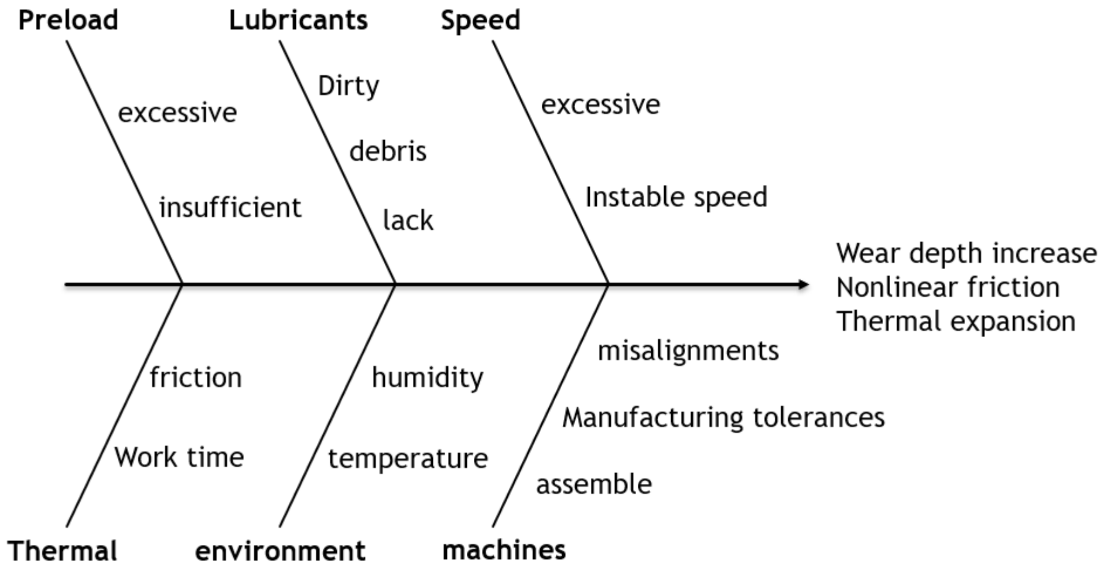

Figure. 1. The scheme of the problem and causes

2. Due to the low relative velocity and large normal force in the contact area between the ball and the raceway during acceleration and deceleration, the lubrication is in mixed or boundary state.

During acceleration, the drive torque increases to a high value and then decreases. Because the lubrication film does not form immediately to protect the contact surface of ball screw, increasing friction requires more torque to drive the shaft of the ball screw system. Since high speed rotation requires more acceleration time, acceleration torque increases as the speed increases. During deceleration, it behaves differently from acceleration, but also requires higher torque to stop.

2.1.2 The wear analysis of friction

The ball surface is smoother than the raceway, so the roughness of the ball and the raceway can be considered as a smooth surface against a rough surface.

If the hard asperity repeatedly ploughs the soft surface along the same direction, unidirectional elements of plastic strain may accumulate with each cycle. In such a process of 'ratchetting failure' or 'incremental collapse', there is evidence that wear occurs by the production of very fine plate-like debris through a mechanism of ductile fracture, evidence of which can be seen in the micrograph of Fig.2.

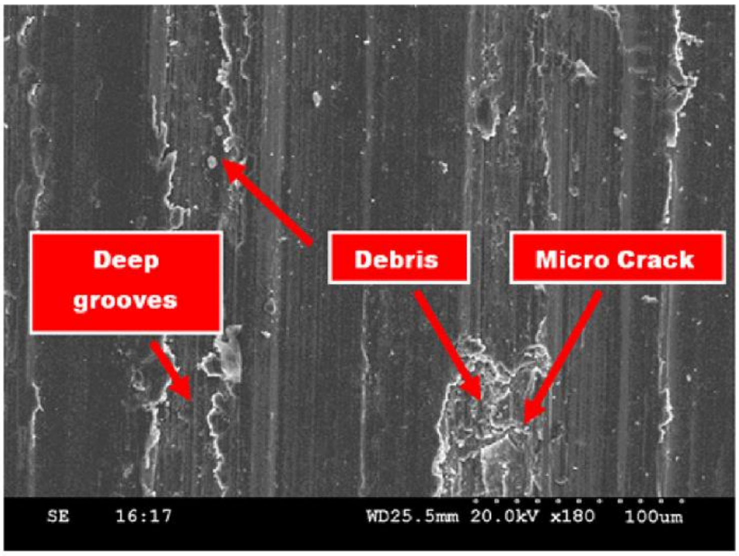

Figure2. Scanning electron micrograph of wear grooves and wear debris

The dry contact based wear analysis method can be used in the acceleration and deceleration steps.

Acceleration varies with rotational speed.

Rotational speed (rad/s)	31.4	62.8	94.2	125.6	219.9	314.2
Acceleration time (s)	0.036	0.055	0.076	0.099	0.16	0.215
Acceleration (m/s^2)	2.78	3.63	3.95	4.04	4.375	4.65

Table 1 [1]

The rotational speed of the screw varies from 31.4 rad/s to 314.2 rad/s [1]. The motion characteristics and transmission performance of the screw at low and high rotational speeds are studied. Acceleration and time increase with the increase of rotational speed, as showed in the table 1.

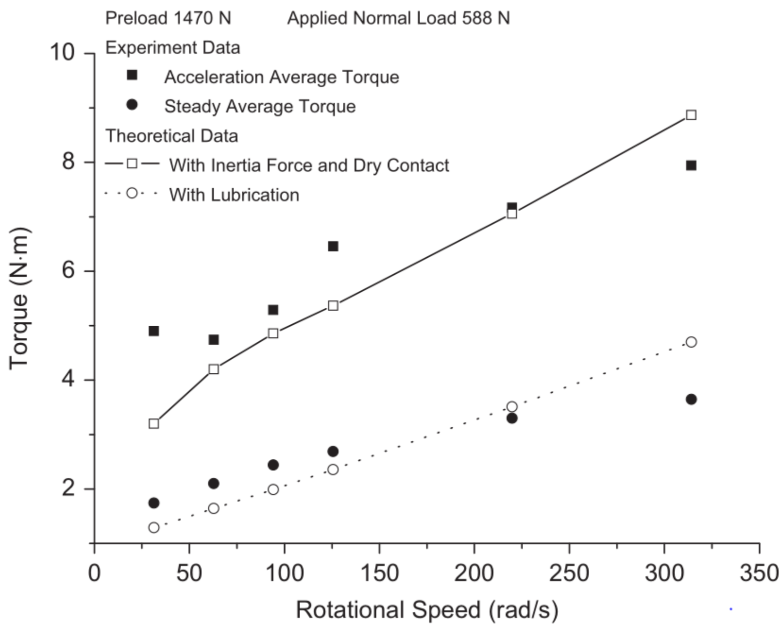

Figure3. The analytical results for the torque are confirmed with experiments considering lubricated and dry contact conditions

Poor lubrication at acceleration makes it possible to assume dry contact between the ball and the raceway. Elastohydrodynamic lubrication model was used to simulate the steady-state process. The analysis results were verified by experiments, as shown in FIG. 2. From the figure we can find that the calculation error is less than 15%, and the dry contact result has a larger error than the lubrication analysis result. Because the actual accelerated lubrication state may be mixed lubrication state or boundary lubrication state, there is a certain oil film on the contact surface.

Based on this concept, the dry contact wear analysis in this study can be applied to acceleration and deceleration steps.

2.1.3 Results and analysis

2.1.3.1 screw and nut

The surface roughness of the nut is much higher than the screw. The surface hardness of the nut is 6.6 GPa, which is also smaller than the screw (7.6 GPa). Varying the plastic ratio with the axial load is also similar to the dimensionless contact force.

The wear rate of ball nut is always greater than that of ball screw. This is because the size of the contact force is small, ball nut relative speed than ball screw contact side.

The wear rate of each contact surface of each contact surface is written as follow.

$$\delta_{wt} = E_c \dot{N} \Delta H$$

δ_{wt}: wear rate

E_c: effective contact ratio (the function of the ratio between plastic contact and normal contact)

ΔH: wear depth of an asperity

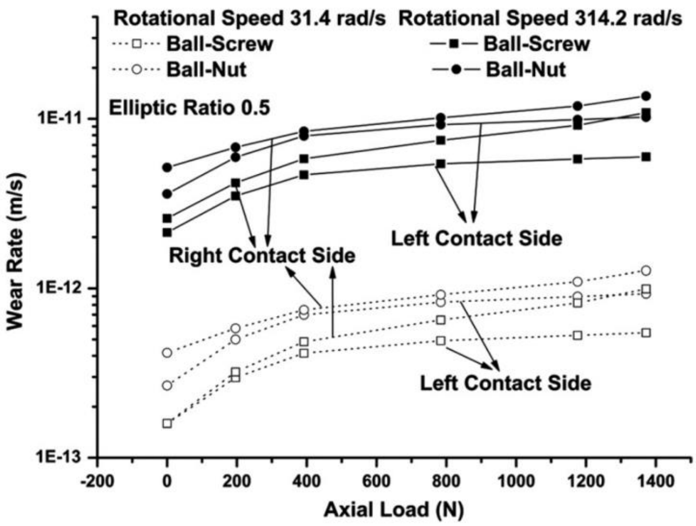

Figure4. Wear rate formed at different contact surfaces varying with axial loads and two rotational speeds

From figure 4, we can see that the wear rate of ball nut is higher than screw. Apart from this, the wear rate of contact surface varies with axial load and rotation speed. The wear rate increases with the increase of axial load and rotation speed. Under low axial load, the wear rate is high and then decreases gradually, especially at left contact side. When raising the axial load, the contact force at the left contact side is decreased, and the contact area is also reduced.

2.1.3.2 preload and rotation speed

The axial wear depth of ball and raceway contact area is determined by the wear rate during acceleration and deceleration. The change of preloading force can also be calculated, as shown in figure 5. When the number of transmission trips is low (below 2000 strokes), the axial wear depth increases rapidly and remains slightly higher after running more strokes. This is called running-in process. The wear frequency $\dot{N}$(which is calculated by sliding velocity and contact area diameter) and the wear rate δ_{wt} increase due to the higher relative speed of high rotating speed. With the increase of axial wear depth, the preload decreases. The rate of reduction of preload also depends on the speed, especially for high speed. This is because high rotation speed require more acceleration and deceleration time. The limit of the preload is decreased by over 30% of the applied value when the ball–screw has failed. To maintain the accuracy of a high-speed ball–screw, the allowable decrease in the preload is 10%. A preload can eliminate the axial backlash and increase the stiffness of a ball–screw, but an excessive preload will increase the friction of the ball–screw and thus decrease its mechanical efficiency

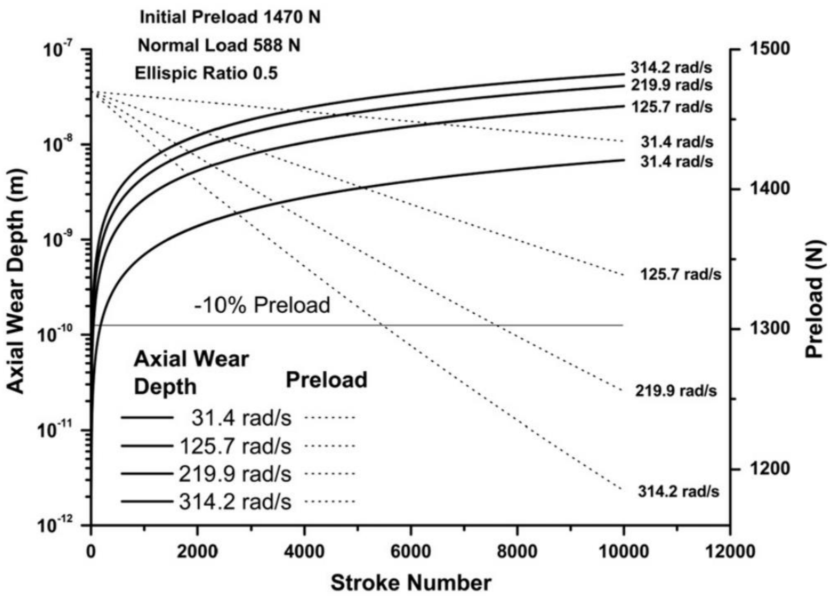

Figure5 Axial wear depth versus preload varying with stroke number and rotational speeds

2.2 Thermal error

2.2.1 The current situation of thermal error

In the 1990 s, the researchers report, precision parts in 40-70% of the error is caused by the thermal error, even now, the industry also does not have too big change.

High speed drive system with ball screw and nut contact area of the friction produce more heat, which leads to thermal expansion and an adverse effect on the machining accuracy. Therefore, the thermal deformation of ball screw pair is one of the important problems to be considered in high precision and high speed machine tools. Thermal behavior model using the finite element method (FEM) was developed, which included heat generation from the main heat source of the ball screw system, convection boundary conditions with ambient air and heat flux between the solid and fluid areas.

2.2.2 The mathematic model

Thermal error is a time - dependent nonlinear process caused by non - uniform temperature variation in machine structure.

The total frictional torque M consists of two parts such as:

$$M = M_1 + M_2$$

where M_1 is the frictional torque due to the applied load and M_2 is the frictional torque due to lubricant viscosity.

$$M_1 = f_1 p_1 d_m$$

$$M_2 = 10^7 f_0 (v_0 n)^{2/3} d_m^3 \quad \text{if} \quad v_0 n \geq 2000$$

$$M_2 = 160 \times 10^7 f_0 d_m^3 \qquad \text{if} \quad v_0 n < 2000$$

f_1 is a factor related to bearing type and load, p_1 is the bearing preload (N) and d_m is the mean diameter (mm) of the bearing. f_0 is a factor related to bearing type and lubricant method and v_0 is the kinematic viscosity (mm^2/s) of the lubricant.

The heating principle of ball screw nut is very similar to that of ordinary ball bearing. The heat mainly comes from the friction between the ball and the nut groove and between the ball and the screw groove. The load on the nut consists of two parts: preload and dynamic load.

2.2.3 The design of experimental

In order to measure the temperature rise and thermal deformation of the ball screw system under the long-term movement of the nut, the arrangement as shown in FIG. 6 was used for the experiment.

As shown in figure.6. a, temperatures at nine points were measured. The two thermocouples (nos. 1 and 8) are located on the rear bearing surface and the front bearing surface respectively. They were used to measure the surface temperature of the two support bearings. The last one (number 9) is used to measure room temperature. Room temperature is recorded to eliminate the effects of environmental changes. These three thermocouples are used for continuous acquisition under moving conditions. The other six thermocouples (no. 2-7) are used to measure the surface temperature of the ball screw. Because the moving nut covers most of the ball screws, the thermocouple cannot be fixed to the ball screws all the time. When a temperature measurement is required, the ball screw stops running and the six thermocouples are quickly connected to the ball screw at the specified position. After collecting the required data, the thermocouple was quickly removed.

There are two way to measure the deformation error. (Because a thrust bearing is used on the driving side of the ball-screw, this end is considered to be fixed)

1. The capacitor probe is mounted on the drive side of the ball screw, and its direction is perpendicular to the side surface, as shown in FIG. B. The probe is used to record the whole thermal deformation of ball screw.

2. The second method is used to measure the thermal error distribution at a given time.

The initial position error distribution is measured by laser interferometer before the feed drive system starts to work.

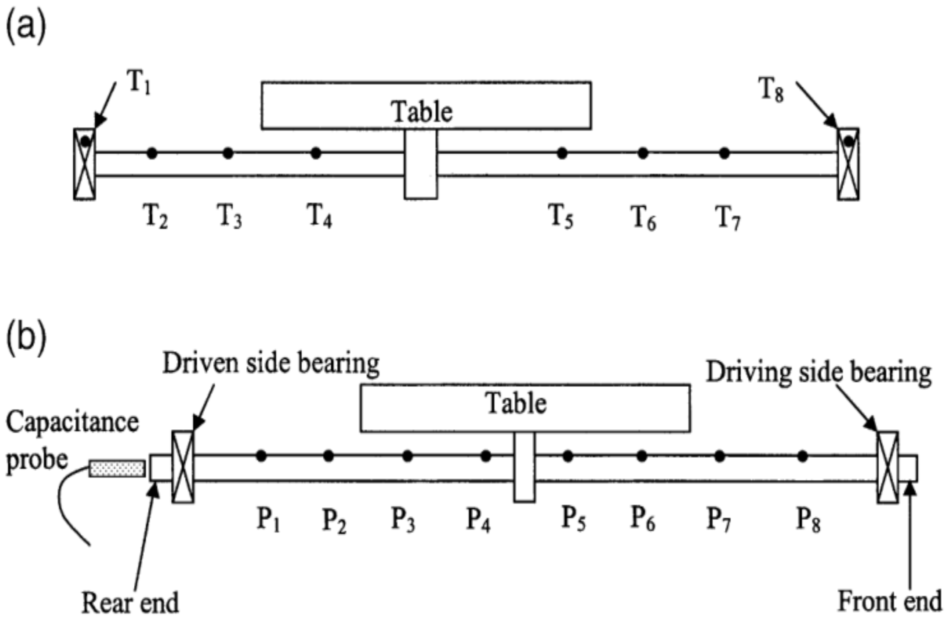

Figure6. Locations of measured points for (a) temperatures and (b) thermal errors.

2.2.4 Result and discussion

Firstly, the preloading force of ball screw is zero, and its thermal performance is studied. Over time, the feeding speed of the feed drive system is 10 m/min. The table will keep running until the temperature and thermal error up to a steady state.

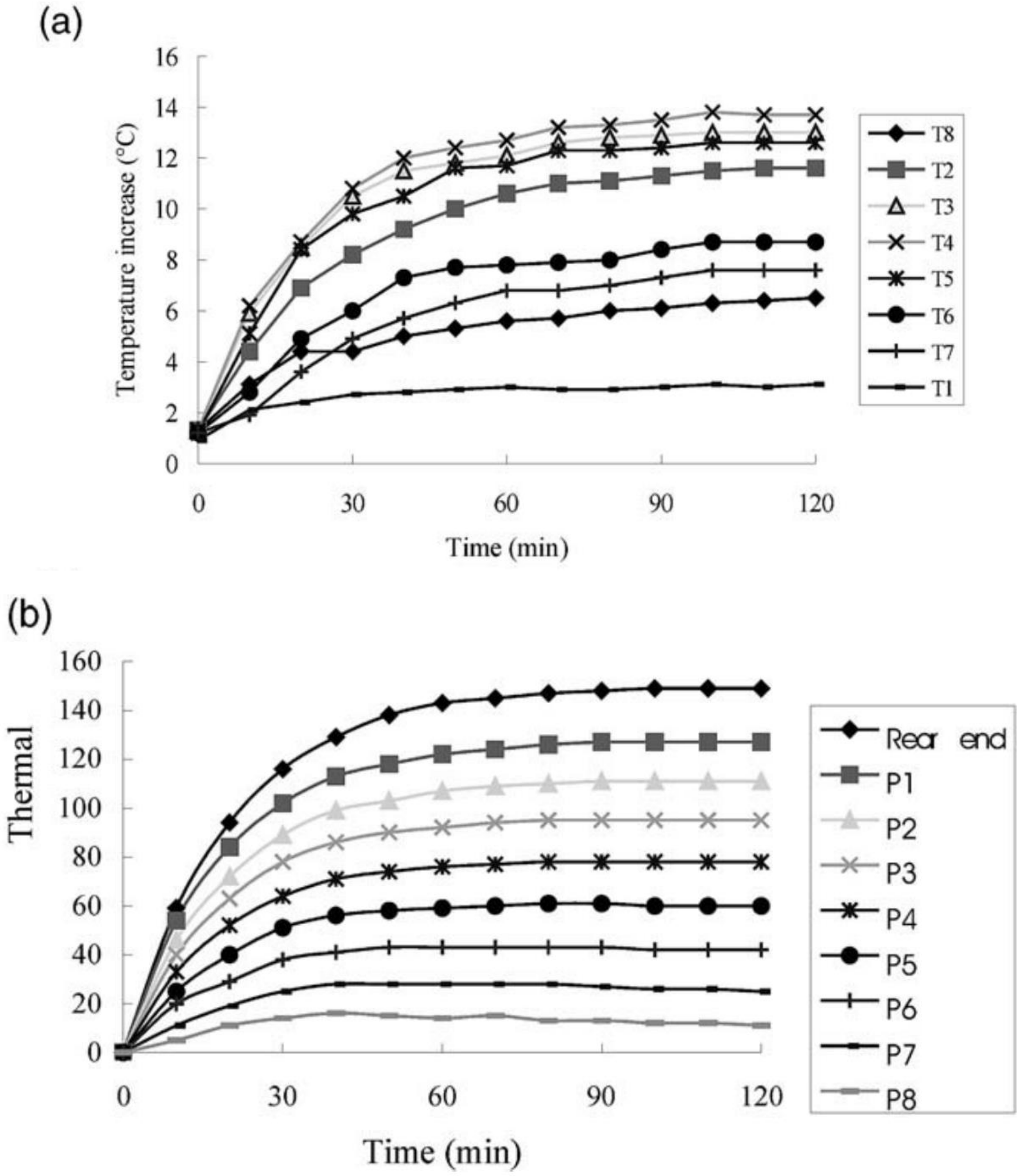

Figure7. (a) Measured temperature increase and (b) thermal error overtime for feed rate of 10 m/min and zero-preload.

Measurements can also be made for feed rates of 15 and 20m/min. The measured data at a steady state are shown in Tables 2, 3.

Preload (kgfcm)	Feedrate (m/min)	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
0	10	3.1	11.6	13.0	13.7	12.6	8.7	7.6	6.5
	15	4.0	14.1	16.2	17.4	16.3	11.1	9.3	8.0
	20	5.7	16.8	20.6	21.0	18.9	12.6	10.6	9.5
150	10	4.6	10.4	13.0	13.2	11.7	8.0	6.4	6.1
	15	5.2	13.6	15.8	16.8	15.3	10.9	9.2	9.0
300	10	7.5	9.4	10.3	10.9	10.0	7.0	6.9	6.5
	15	9.1	12	13.1	13.8	12.8	8.8	8.7	9.5

Table 2. Temperature distribution at steady state with different preloads and feed rates (unit: °C) [4]

Preload (kgf·cm)	Feedrate (m/min)	Rear end	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
0	10	149	127	111	95	78	60	42	25	11
	15	221	181	161	139	117	94	71	49	21
	20	266	227	207	178	151	122	92	66	44
150	10	92	70	57	43	28	15	0	−14	−26
	15	113	97	80	61	40	21	1	−16	−32
300	10	62	52	42	30	17	5	−7	−17	−27
	15	76	64	50	34	20	6	−8	−21	−33

Table 3. Thermal error distribution at steady state with different preloads and feed rates (unit: µm) [4]

From the diagram and data above we can make the conclusion for the first:

1. The higher the feeding speed, the greater the friction heat between the ball screw and the nut contact surface. The friction heat generated by the support bearing and the motor also increases with the increase of feed speed. Therefore, the temperature of ball screw increases with the increase of feed velocity. The table travels over the middle part with a 600 mm stroke. The central part of the ball-screw reveals a higher temperature increase. Support bearings do not have high temperature increase because the bearing preload is zero.

2. Higher rotation speed will bring greater thermal expansion of ball screw. The

temperature in the middle of the screw increases and the thermal expansion is slightly larger. However, this phenomenon is not obvious. The thermal error at certain specified points of the ball screw is approximately proportional to the distance between the point and the front end (the motor drive side of the ball screw).

Secondly, the ball-screw preload was set at 150 kgf·cm and its thermal characteristics were studied. temperature variations around the feed drive system and thermal errors are shown over time for feed rates of 10 and 15 m/min.

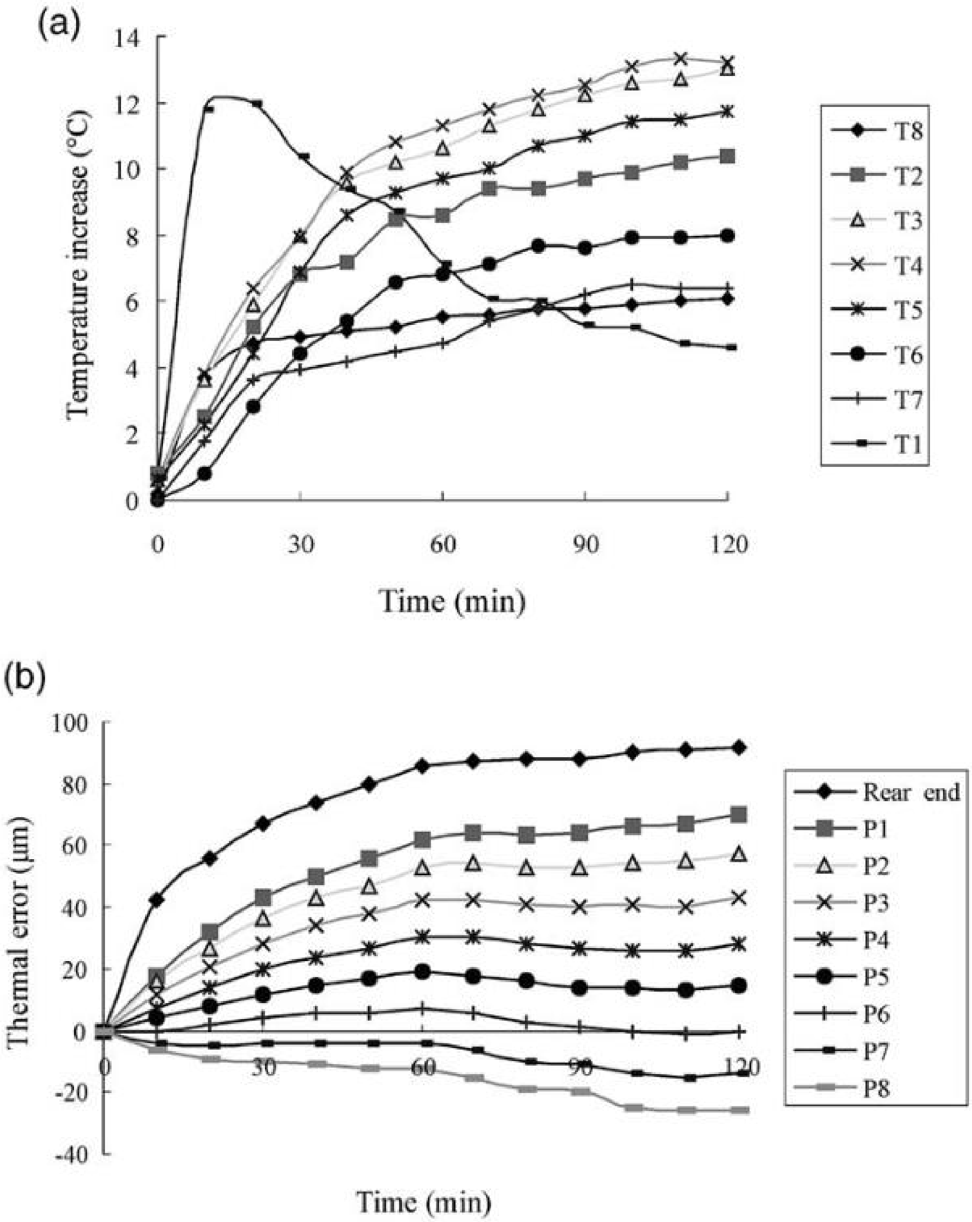

Figure8 (a)Measured temperature increase and (b) thermal error over time for feed rate of 10

m/min and preload of 150 kgf·cm.

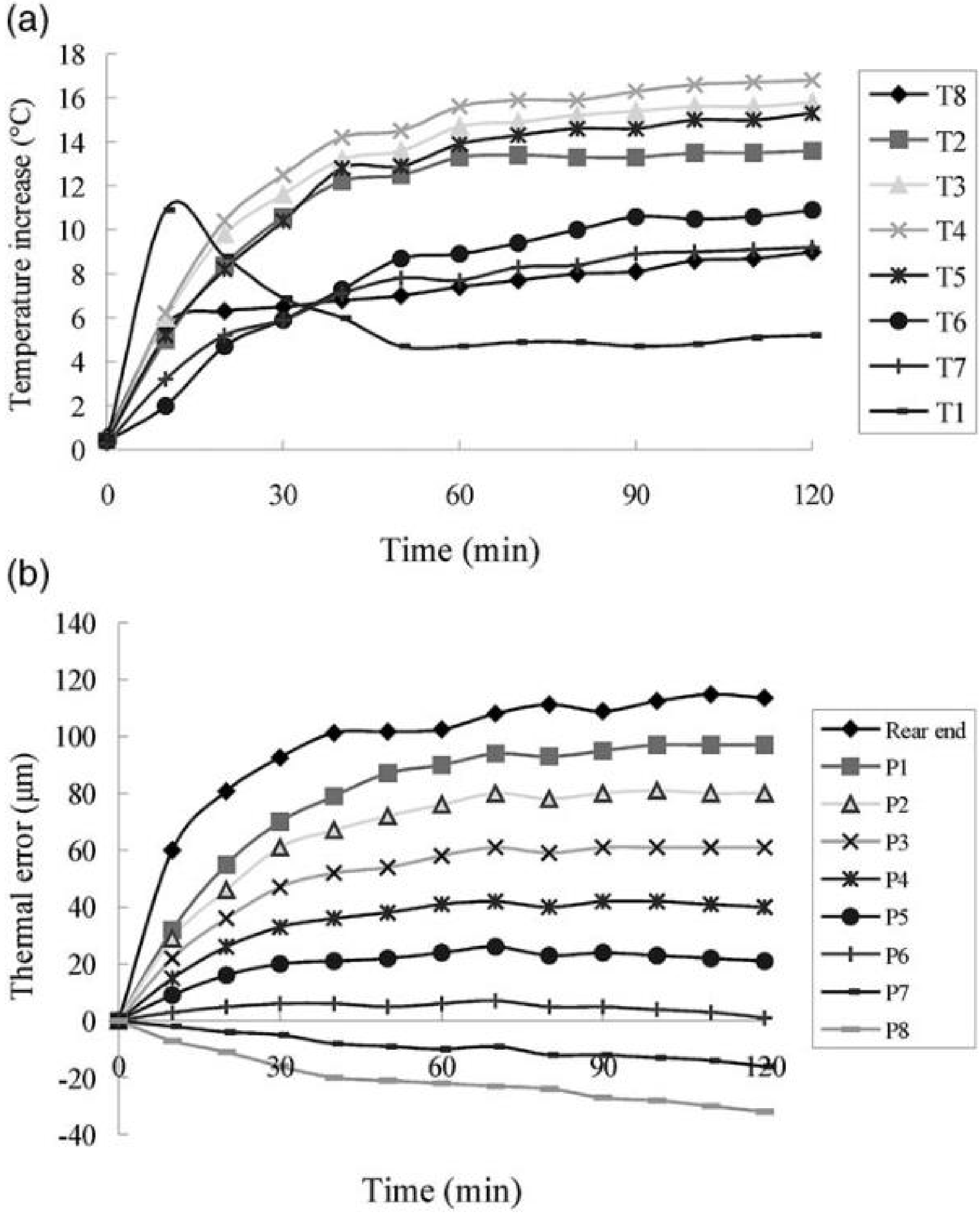

Figure9 (a)Measured temperature increase and (b) thermal error over time for feed rate of 15 m/min and preload of 150 kgf·cm.

From above diagram we can find two interesting phenomenon for the secondly:

1. The temperature rise of the measured point gradually increases until the temperature of the ball screw reaches a stable state, except the temperature rise of the driven side bearing. The temperature of the bearing reaches its maximum rapidly and then gradually decreases.

2. The thermal errors of P6, P7 and P8 are negative at the steady state. This means that these three points move to the drive side due to thermal expansion, while the other points move to the drive side. In addition, the thermal error of p4 to p8 decreases gradually after 60 minutes.

The reason for those two phenomenon are descripted as follow:

1. The preload of ball screw increases the preload of driven side bearing. When the feed drive system is running, the temperature of the driven side bearing increases sharply due to the increase of the preload. However, the thermal expansion of the ball screw relaxes the ball screw and reduces the pretension of the bearing on the driven side. As a result, the temperature gradually drops to a steady state.

2. Feed drive system starts running and ball screw expands. The expansion loosens the preload of the ball screw and the bending deformation of the two bearing blocks. Therefore, the point on the drive side is close to the motor, so the thermal error is negative; however, the point on the drive side moves to the free end, so the thermal error is positive.

Finally, the ball-screw preload was set to 300 kgf·cm and its thermal characteristics were studied. The tendency with a 300kgf·cm is similar to that with a 150 kgf·cm. Measured data are shown in Tables 2 and 3.

2.2.5 The conclusion for the thermal error

From the experiment and the results we can collect 4 conclusion which are descripted as follow:

1. The accuracy of the position is improved, and it is closer to the drive side of the ball

screw. The thermal error increases with the distance of the driven side of ball screw. The maximum thermal error occurs on the driven side of the ball screw (free end). This value can be used as the total thermal error of the ball screw and can be measured with a capacitive probe.

2. The preload of ball screw increases the temperature of two supporting bearings, especially the driven side bearings. The reduced surface temperature of the ball screw is due to the thermal effect of relaxing the preload, which reduces the friction between the nut and the ball screw.

3. The thermal expansion of ball screw increases with the increase of feed velocity, thus increasing the position error. However, the increased preloading reduces the thermal error and improves the position accuracy of the feed drive system.

4. If ball screws are preloaded, the two bearings may bend. Thermal expansion loosens the pretension of ball screw and the bending deformation of two bearing blocks. Therefore, when the point on the motor side is close to the motor, the thermal error is negative. However, when the point on the free side moves to the free end, the thermal error is positive.

2.3 The efficiency of ball screw

2.3.1 the lose of efficiency

High translation ball screw must have higher positioning accuracy and stiffness by applying higher preloading force. However, the applied preload increases initial drive torque, friction, and heat. Therefore, important design criteria for high translation preloaded ball screws include low drive torque and minimum sliding motion to achieve maximum mechanical efficiency.

Contact geometry and friction are the main factors affecting the mechanical efficiency of ball screw pair. The contact geometry and friction in the contact area vary greatly as the screw works at high or low speeds. In general, 1000 RPM is the dividing point between two velocity subregions. The effect of high revs results in a significant increase in the centrifugal force of the ball and the sliding motion that forms on the ball and track. The centrifugal force of the ball is determined by the function of the screw speed and the axial load applied on the nut. The increase of ball centrifugal force leads to the decrease of normal force at ball screw contact point, but the increase of normal force at ball nut contact point. The contact Angle will change to different degrees, and other parameters (normal force, friction, slip rate, etc.) will also be affected. In any of these two subregions, the following parameters of two ball orbits are obtained under axial loading: contact Angle, pure rolling point, driving torque and mechanical efficiency.

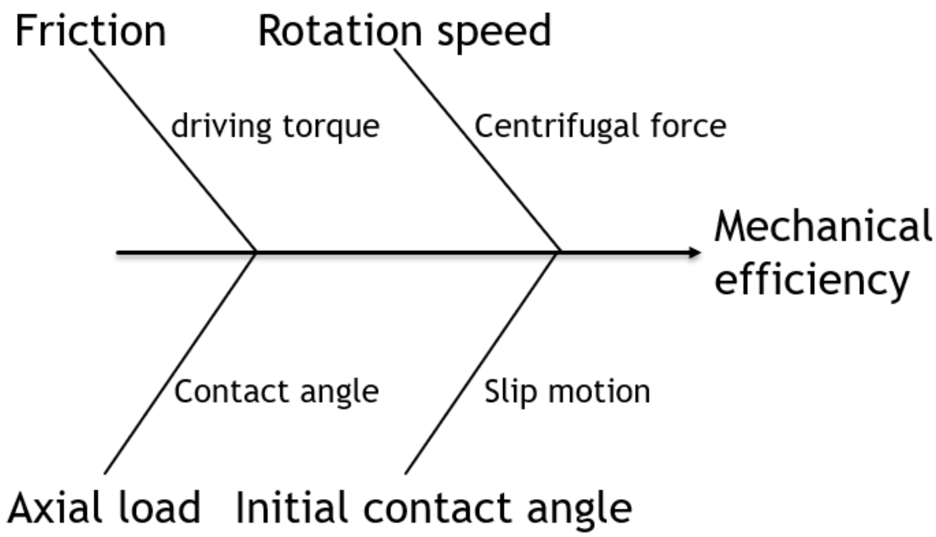

Figure10 Ishikawa diagram for the efficiency of ball screw

2.3.2Mathematic model

Adjust the ball's preload by offsetting the center distance between the nuts on both fairways [10]. Assume an axial load is applied to the left of the nut at the end of the ball screw and parallel to the screw axis. The single-nut preloading in this study is accomplished by supplying the nut with offset pitch, as shown in the Fig.11.

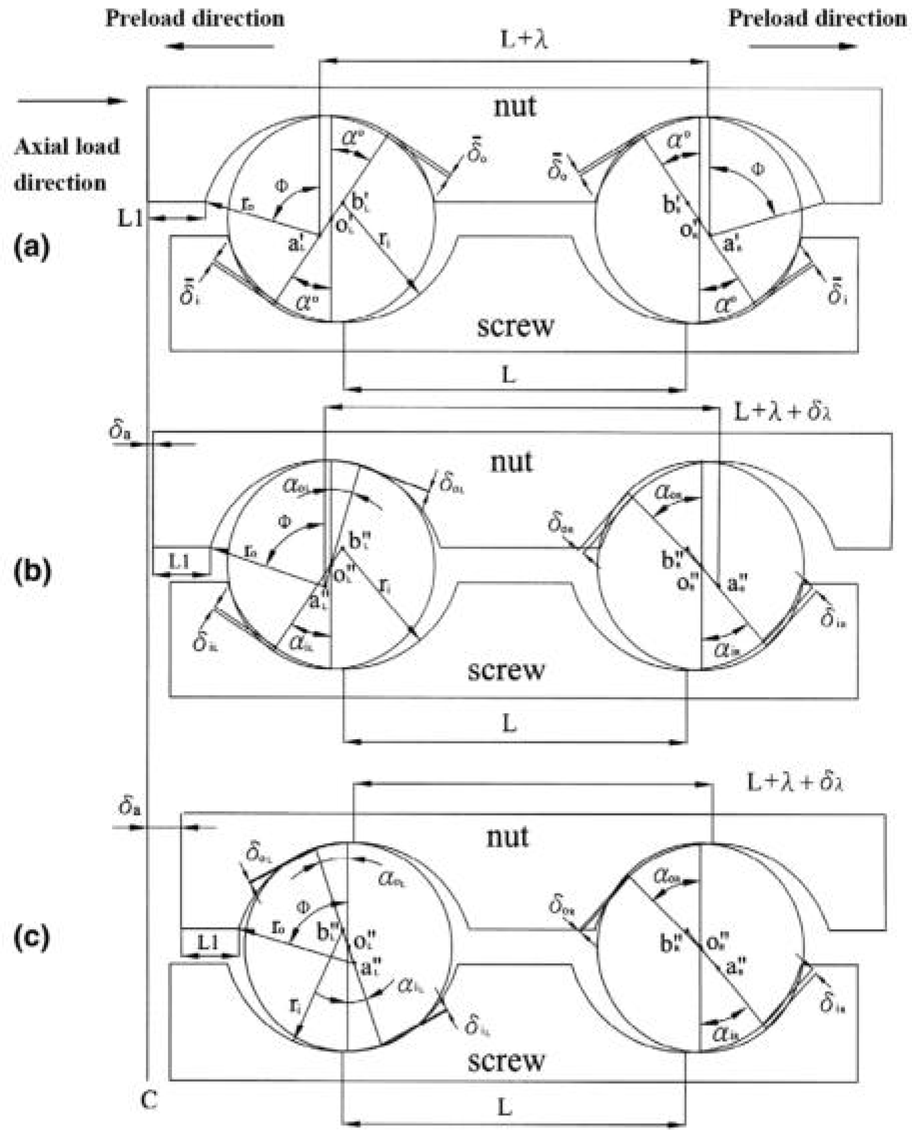

Figure11 The ball screw mechanisms with an axial load as well as different preloads: (a) non-axial load; (b) preload greater than applied axial load; (c) preload lower than applied axial load.

When an axial load is applied to the left end of the nut, the offset λ will produce anelastic deformation $\delta_\lambda$at the left end of the nut (see Fig.(b) and (c)). When the ball is trapped between the nut and the screw, elastic deformation occurs in the two elliptic contact areas where the ball contacts the screw and the nut. The largest elastic deformations in these two elliptical contact areas are $\overline{\delta}_o$ and $\overline{\delta}_i$, respectively. The Angle formed between the n axis and the line connecting the center of either of the two ellipse contact areas is the contact Angle. The contact angle formed at the nut (α_o) is different from that formed at the screw (α_i), unless no axial load is applied. If an on-zero axial load is applied, either α_o or α_i formed on the right ball track will be different from that formed on the left track.

All four contact angles have the same value until axial loading is applied to the ball screw system. In this case, the contact angles formed in each contact area are the same and are called initial contact angles α^{o}. However, the preloading force in the nut causes the line connecting the center of the two elliptic contact areas formed in the right fairway to tilt to the left at an α^{o}, while the line in the left fairway will tilt to the right at the same Angle. When an axial load is applied (but is less than the preload), the contact angle (α_{oL}) formed in both the nut and the left ball track will be reduced, moving the contact centre towards the n-axis. However, the contact angle (α_{oR}) formed at the nut, as well as on the right ball track, will be moved far away from the n-axis. The contact angle α_{oL} will continue to decrease until the axial load approaches the preload. When this axial load almost reaches the preload, the deformations δ_{oL} and δ_{iL}, which originally existed on the left ball track, will disappear, and the normal force acting on the contact area becomes zero. If the axial load applied to the system is greater than the preload, the contact point in the contact area of the left ball nut will move to the other side of the n axis. This abrupt shift of the contact angle α_{oL}, when the axial load is almost equal to the preload, indicates that a solution does not exist for several parameters.

Consider the possibility of a pure rolling point in each contact area and use it to define rotational angular velocity and rotational angular velocity. The different positions of the pure rolling point can be used to define the movement of the ball screw contact area. When the position of the pure rolling point is close to the center of the contact area, the motion behavior in this area is lower. The ball-screw and the ball-nut contact areas are assumed to have different pure-rolling points. Points 4, 5, 8 and 9, as shown in Fig.12, denote these four pure-rolling points.

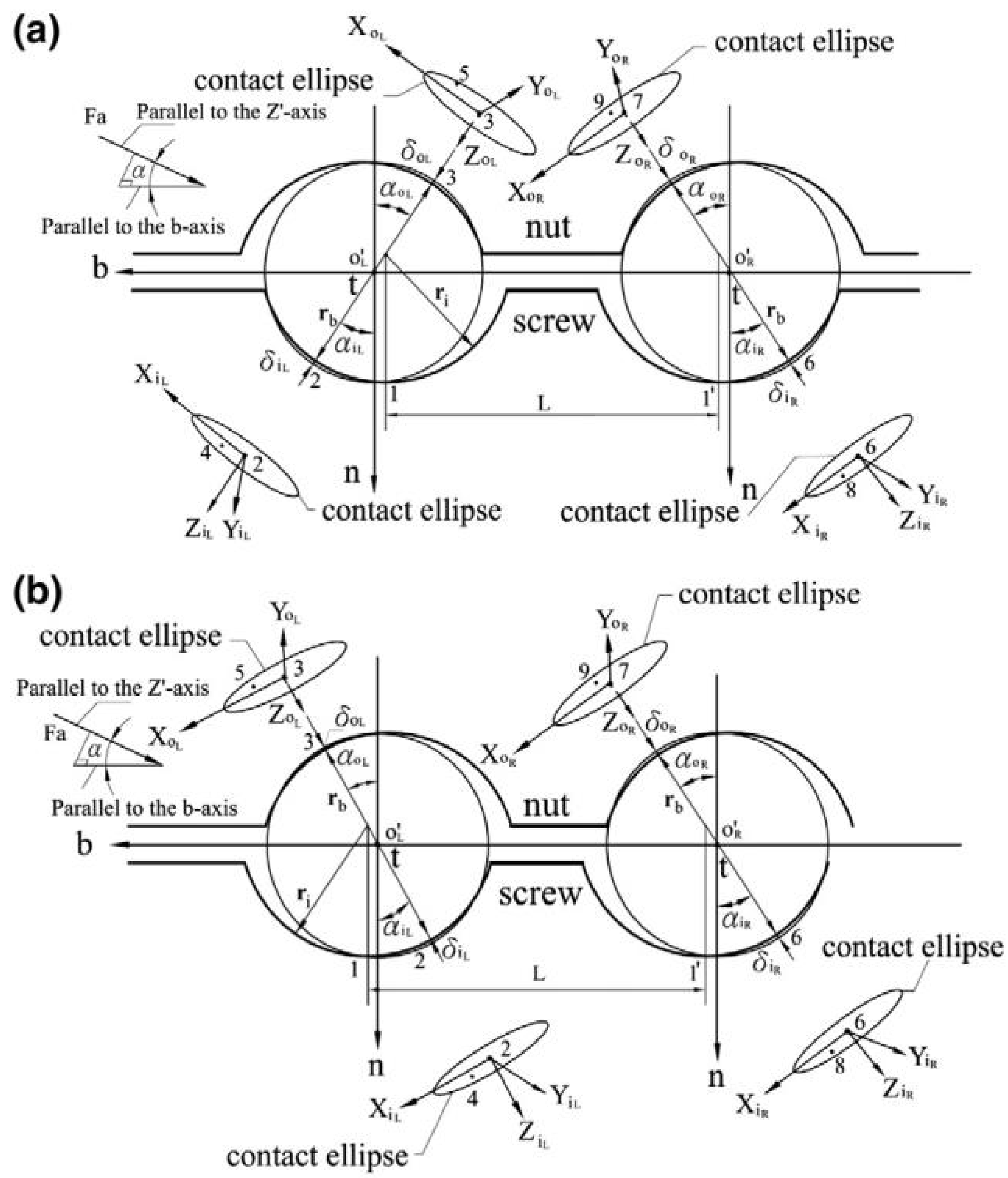

Figure12 The positions of pure-rolling points and ball centres at the contact areas: (a) the axial load smaller than the preload; (b) the axial load greater than the preload.

Fig.12 shows how the distance between the pure-rolling point and the contact centre vary with rotational speed and axial load. The distance between the ball screw contact area and the ball nut contact area is always greater than the distance between the ball screw contact area and the ball nut contact area. Therefore, the distance formed on the left contact side is also greater than the distance formed on the right contact side, which means the sliding motion on the left contact side is more serious.

When the axial load is less than the preload, the distance of the left contact side increases with the increase of the axial load. However, with the increase of axial load, the distance on the right contact side decreases slightly. When the axial load is larger than the preload, the distance between the left and right contact sides decreases with the increase of the axial load, because the increase of the normal force formed in the contact area can restrain the sliding motion and reduce the distance between the pure rolling points and the contact center. The left contact side loosens at first, and then tightens when the axial load increases. The right contact side remain tight at all times. In the figure12, the distance changes slightly as the speed increases. When the axial load applied is close to the preload, the distance between the pure rolling point and the contact area of the left ball nut and the contact center at high speed is slightly smaller than that at low speed, but the behavior is opposite when operation at the ball screw contact side. This is due to the significant increase of centrifugal force during high speed rotation and the fact that the normal force applied in the contact area of ball nut is larger than that formed in the contact area of ball screw.

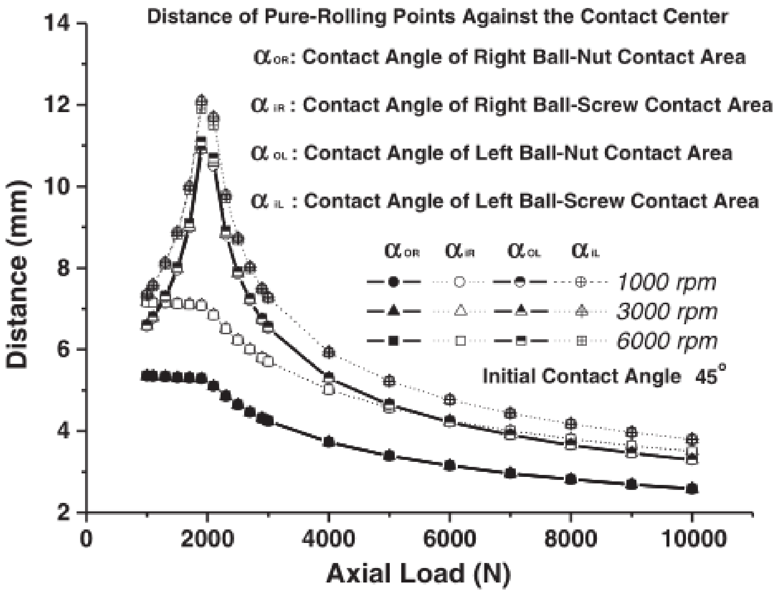

Figure13 Variation in the distance of pure-rolling points against the centre of contact area of the ball-nut and ball-screw contact areas with axial load and rotational speed.

Fig.13, shows that an increase in the initial contact angles, α_o , can effectively reduce the distance between the pure-rolling points and the contact centre, which reduces the slip motion occurring at the contact areas.

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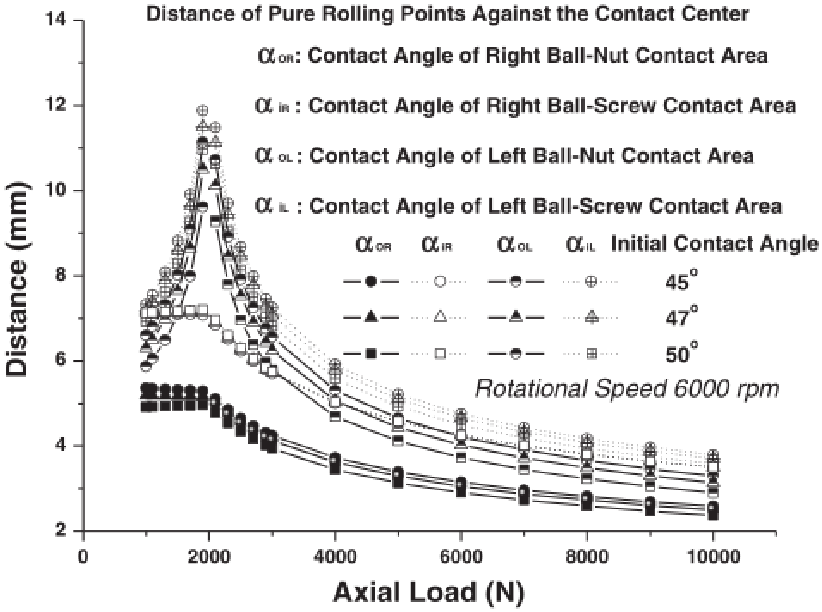


Figure14 Variation of the distance of pure-rolling points against the centre of contact area of the ball-nut and ball-screw contact areas with axial load and initial contact angles.

The ball passing frequency is calculated from the number of balls passing through the returning tube of a nut over a period of one second. The revolutional angular speed of the balls, ω_m , which is also denoted by the orbital angular speed of balls, is expressed as a function of the passing frequency of the balls. The equation for the balls' passing frequency, B_f , is written as follow:

$$B_f = \frac{\omega_m b_n}{2\pi}$$

where b_n is the number of balls in a cycle. Using the accelerometer to obtain vibration signals near the return tubing cover on the flange, as shown in Fig14. When the ball passes through the return tube, the accelerometer can detect the impact signal between the ball and the return tube. However, other vibration signals, such as those from friction and impact between two adjacent balls, are mixed with shock signals. These vibration signals were analysed over the time interval, and Fast Fourier Transform (FFT) methods were used to obtain the ball's passing frequency; their values were then verified by analysing the numerical results.

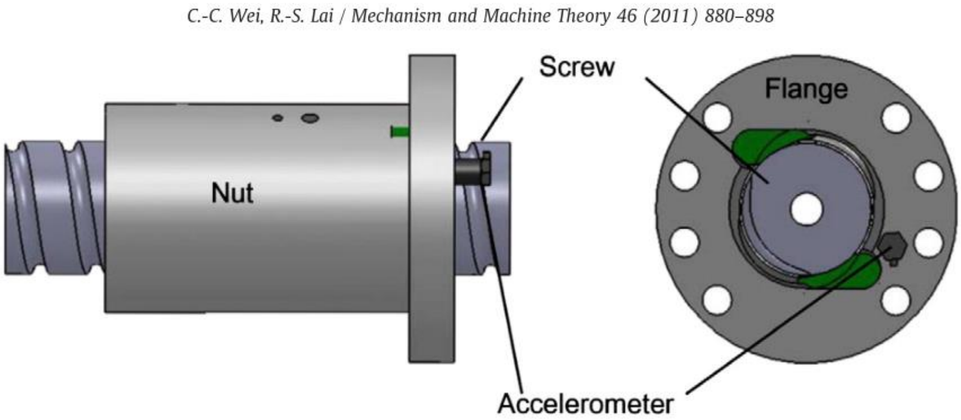


Figure15 A sketch of measuring the passing frequency of balls

The mechanical efficiency of the ball screw could thus be determined with the known driving torque and thrust force. The mechanical efficiency of a ball-screw system is defined as the ratio of the work output, which is related to the axial load and linear velocity, to the work input produced by the driving torque. The work output is related to the load applied to the nut in the axial direction, given as：

$$W_{Fa} = F_{ap} V_{axial} = \frac{F_{ap} \omega L}{2\pi}$$

where V_{axial} is the linear velocity in the axial direction of the nut, and F_{ap} is the applied axial load. The moment input that relates the frictional forces and normal forces at the screw contact areas is given as：

$$M_{input} = M_{il} + M_{ir}$$

where M i L and M i R denote the moment inputs required to overcome the frictional torques generated at the ball-screw contact areas formed on the left and right sides, respectively.

he mechanical efficiency, η, of a ball screw system is thus defined as:

$$\eta = \frac{W_{Fa}}{M_{input} \omega} = \frac{F_{ap} L}{2\pi M_{input}}$$

2.3.3 Results discussion

When the axial load approaches the preload (8550n) [10], the mechanical efficiency also decreases, while when working in the heavy-load area, the mechanical efficiency slightly increases to the asymptotic value. The comparison between experimental results and theoretical analysis results shows that the difference of mechanical efficiency between the two value is less than 3% under the action of larger axial load. The prediction of ball screw pair performance by this model is verified.

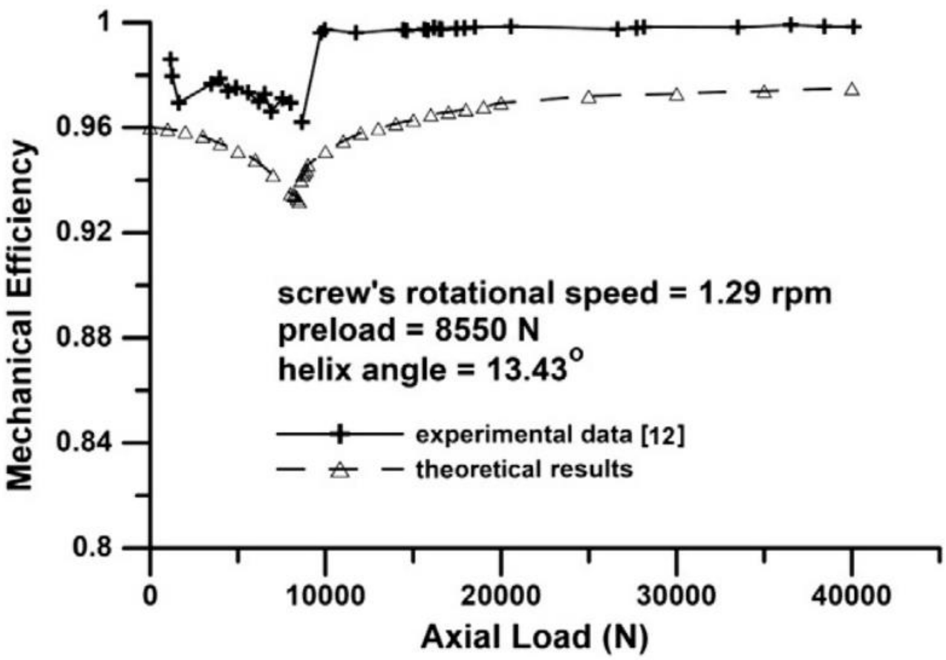


Figure 16 The change of efficiency by varying axial load.

The mechanical efficiency of the ball screw pair is inversely proportional to the torque input required for the ball screw pair to rotate under an axial load. The figure.16 shows the change of theoretical mechanical efficiency and driving torque with axial load and rotation speed. With the increase of axial load and decrease of rotating speed, the mechanical efficiency increases. The increase in the axial load can increase the numerator of η and also increase the driving torque in the denominator. The increase rate of axial load is higher than that of driving torque, which improves the mechanical efficiency under axial load. Increasing the speed will cause more slippage and friction, thus increasing the driving torque and reducing the mechanical efficiency.

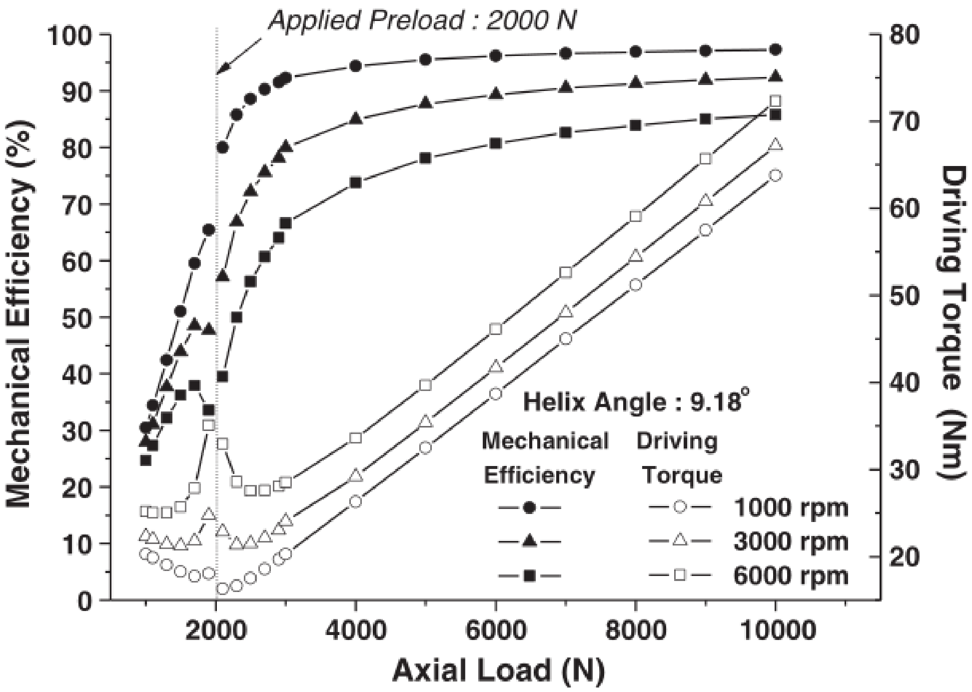


Figure17 Variation of mechanical efficiency and driving torque of ball screw with axial load and rotational speed.

From the above discussion, an increase in the initial contact angle of a ball screw can decrease the distance between the pure-rolling point and the contact centre; thus, slip motion is decreased. Also, the driving torque decreases and the mechanical efficiency increases. Fig.17 shows how the mechanical efficiency increases and the driving torque decreases by increasing the initial contact angle when the rotational speed is fixed at 6000 rpm [10]. An interesting trend occurs when the axial load is 1900 N: the mechanical efficiency suddenly drops sharply. The efficiency is improved by increasing the initial contact angle, which is important for the high-speed translation ball screw system. When a ball-screw system accelerates from zero to a steady value or decelerates to zero, a heavy axial load results from the inertial effect of the ball-screw system, and the system can operate at a critical region near the preload, where large variations in driving torques are observed. Severe sliding on the left ball contact side may cause wear in the contact area. The results show that increasing the initial contact Angle of the high-speed ball screw system can effectively reduce the sliding motion and driving torque, and thus improve the mechanical efficiency.

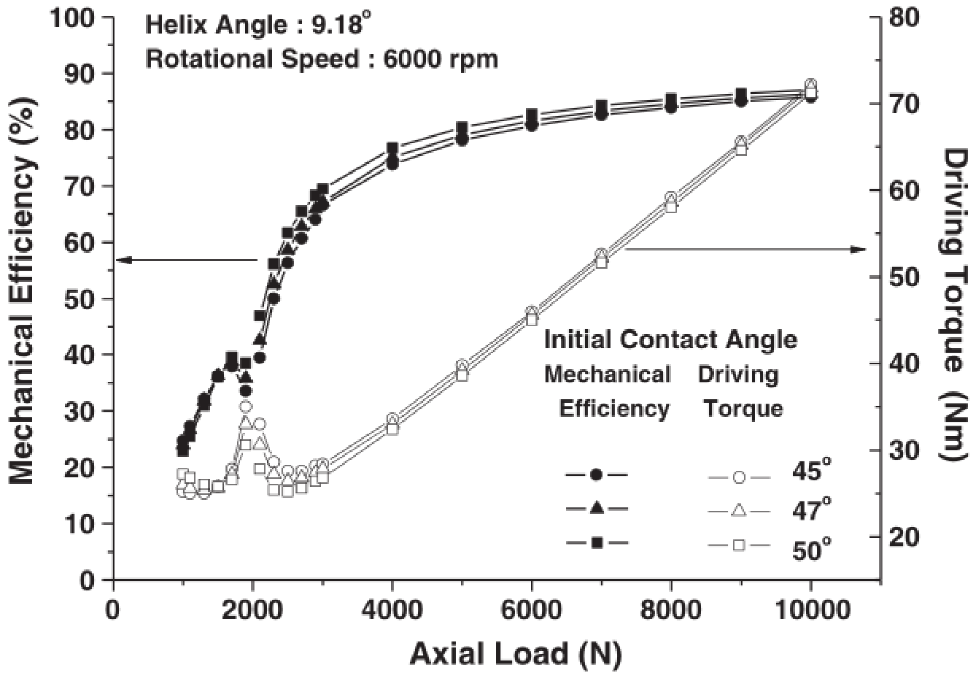


Figure18 Variation of mechanical efficiency and driving torque of ball screw with axial load and initial contact angle at high rotational speed.

2.3.4 Conclusion

1. Due to the decrease of normal force and the sliding motion in the contact area on the left side, the mechanical efficiency decreases significantly when the axial load approaches the preloading.

2. When the axial load approaches the preload, the contact Angle, the distance between the pure rolling points, the contact center on the left ball contact side and the driving torque increase significantly. When the axial load approaches the applied preload, the normal force in the contact area of the left ball decreases. Therefore, when the screw runs at high speed, the influence of sliding motion on centrifugal force increases. The increase of sliding motion also leads to the increasing distance between the pure rolling point and the contact center of the contact area. Meanwhile, the driving torque increases with the increase of rotation speed.

3. The distance between the pure rolling point and the contact center decreases with the increase of the initial contact Angle. Small distance can improve the mechanical

efficiency of ball screw pair and reduce the driving torque of ball screw pair, especially when the axial load is close to the preload. Reducing sliding motion may reduces wear in the left contact area and prolongates the life of the off-set preloaded high-speed ball screw system.

Chapter 3: The impact of maintenance

3.1 The introduce of maintenance

3.1.1 The development of maintenance

The purpose of maintenance is that preventing equipment performance deterioration or reduce the probability of equipment failure, the technical management measures shall be carried out in accordance with the provisions of the pre-specified plan or corresponding technical conditions, The maintenance cost play more and more important role in the total operating costs of the most plants. Take American for example, in 1981, the American companies spent more than 600 billion dollar to maintain their core plant systems. After 10 years, the cost of maintenance increase a little bit to 800 billion dollar. However, in 2000, the costs suffer a huge increase to 1,2 trillion dollor [8]. The problem is that almost one third of the costs are wasted because of the inefficiency maintenance. Therefore, it's important to improve the efficiency of the maintenance for the mechanical industry.

The development of maintenance divided into 5 stage:

1. Before 1950 the maintenance of plants is breakdown maintenance, breakdown maintenance means the plants will keep operation until it breaks down to fix it, and even now, when the stop-loss of production equipment is negligible, a breakdown-maintenance plan can be adopted. It is difficult to plan a repair job if it happens suddenly. Therefore, it is easy to go against the distribution and arrangement of personnel, materials and equipment. However, on the whole, if this efficiency for the suddenly problem can be ignored, breakdown-maintenance can be adopted.

   Furthermore, when the mean time between failures (MTBF) is not fixed, the mean repair time (MTTR) is short and the cost of regular component exchange is high. In this case, post-maintenance can also be adopted.

2. The pants of Amercian begin to use prevention maintenance around 1950. This approach is to maintain the equipment before it fails. Preventive maintenance is a method adopted to prevent downtime caused by sudden failure of equipment. It is the way to replace parts or unitsat each interval time according to the economic point of view. The interval of preventive maintenance is determined by the size or life of the equipment, and it can be performed by regular spot check, repair or overhaul once a year or once every six months or once a month or once a week. Too much preventive maintenance will produce uneconomical waste. preventive maintenance plan is set up according to the post-repair cost or the combination of production and production target achievement status and running rate.

3. In 1960, the productive maintenance was introduced. The purpose of productive maintenance is to ensure the economic and productivity of the plants. This method is a way which integrates the Cost (LCC: life cycle Cost) of the equipment or all costs incurred to maintain the equipment during the whole operation process with the degradation loss and justification, and then decides how to carry out the maintenance. Generally, there are two ways that can be choose. The first one is correct maintenance, in order to make the maintenance and repair of the equipment easier. Further, in order to make the equipment improvement without repair and maintenance, that is to say, this method is to improve the productivity of the equipment by the technical improvement of the equipment. Apart from this, the second way is maintenance prevention. In order to radically reduce the maintenance cost of equipment, rather than just thinking about how to maintain it, it is better to build equipment that does not need maintenance or to consider maintenance when it is purchased. This idea maximizes the ease and cost of operation and maintenance of equipments.

4. Since 1970 it has became total productive maintenance which is the company-

wide production maintenance involving the activities of a small group of autonomous operators. In 1971, Denso published an article entitled "total productive maintenance". It is pointed out that production prevention (maintenance) is not only the responsibility of office Staff, but also the Total prevention of all Staff, including all operating layers, management and operators. The management layer is responsible for promoting production and maintenance. All operators should participate in the activity with enthusiasm. Even though it may not be mature and perfect, this is the sign of the birth of innovative TPM activity.

5. Predictive maintenance became popular in 1980. Predictive maintenance is to diagnose the deterioration or performance of the equipment, and then carry out maintenance and maintenance activities on the basis of the diagnosis. Therefore, it is the premise to correctly and accurately grasp the deterioration of the equipment. Observing degraded states and maintaining them when they really need to be maintained is the condition-based maintenance. With the quantitative grasp of the condition of equipment and the improvement of equipment fault diagnosis technology, there has recently been a transition from the point inspection, search and repair based on time to the judgment and countermeasures based on the state of equipment.

3.1.2 Preventive Maintenance Management

There are many definitions of preventive maintenance, but the main feature of preventive maintenance is time driven, which means maintenance tasks are based on running time or operating hours. Figure 19 illustrates the example of the statistical life of a machine - train. The mean time to failure or bathtub curve shows that the new machine has a high probability of failure, due to installation problems, in the first few weeks of operation. The probability of failure is relatively low for an extended period this initial period after time. After this normal machine life cycle, the probability of failure increases sharply with the running time. In preventive maintenance management, arrange machine maintenance or repair according to mean time to failure(MTTF) [8] statistics.

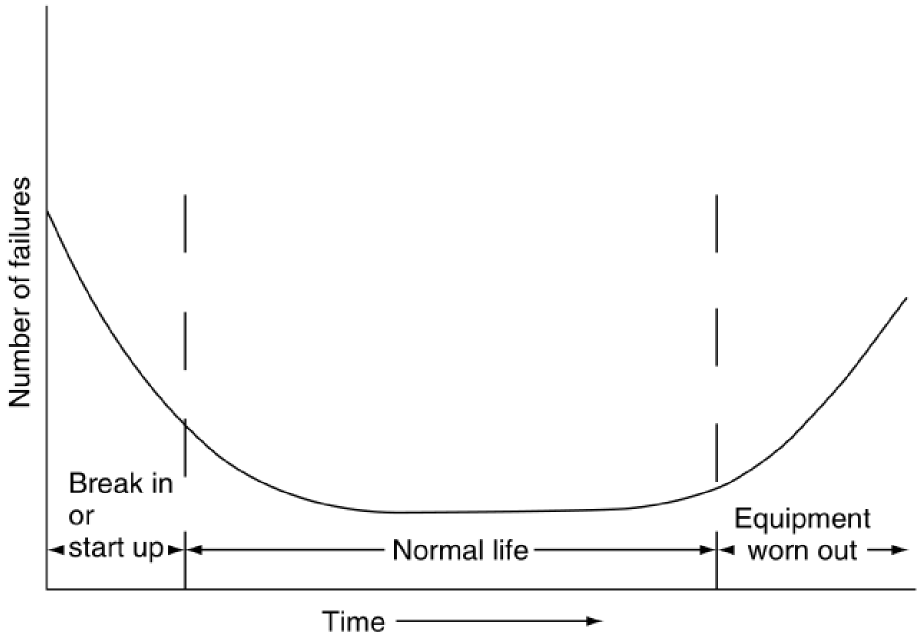


Figure19 The mean time to failure (bathtub curve)

The actual implementation of preventive maintenance varies widely. Some procedures are very limited, including lubrication and minor adjustments. More comprehensive preventive maintenance schedule the repair, lubrication, adjustment and machine rebuilds of all key machinery of plants. All of these preventative maintenance common denominator programs are scheduling guidelines. The comprehensive preventive maintenance management procedure assumes that machines will be degraded to specific classifications within their typical time frame. For example, a single-stage, horizontally split case centrifugal pump must be reinstalled after 18 months of normal operation. When using preventative management techniques, the pump will be removed from the pump after service and rebuilt after 17 months of operation.

The problem with this approach is that operating mode and system or plant specific variables directly affect the normal life of the machine. Mean time between failures will be different for pumps that are treated with water and one that is treated with abrasive slurry. Normal results use Mean time between failures statistics to schedule either unnecessary maintenance or catastrophic failure of unnecessary maintenance. In this case, the pump may not need to be reinstalled for 17 years. As a result, labor and materials used for repairs are wasted. The second option is preventive maintenance, which costs even more. If the pump failed 17 months ago, we had to use a run-to-failure repair technique. An analysis of the maintenance costs shows that the cost of breakdown maintenance will usually 3 time higher than the cost of maintenance of the scheduled basis.

3.1.3 Predictive maintenance

The common definition of predictive maintenance is that regular monitoring of the mechanical condition of the fleet will ensure a maximum interval between maintenance and minimize the number and cost of unplanned downtime caused by machine-train failures. Predictive maintenance is able to improve productivity, product quality and overall efficiency of our manufacturing and production plants. Predictive maintenance is not a predictive maintenance tool for vibration monitoring or thermal imaging or lubricant analysis or any other nondestructive testing technology being sold. Predictive maintenance is a philosophy or attitude that, simply put, optimizes the operation of the entire plant by taking advantage of the actual operation of the plant's equipment and systems. A comprehensive predictive maintenance management plan utilizes the most cost-effective combination of tools, namely vibration monitoring, thermal imaging, tribology, etc., to obtain and, on this basis, analyze the actual operation of the plant's key systems and arrange all maintenance activities as required. Predictive maintenance, including a comprehensive maintenance management plan, optimizes the availability of process machinery and significantly reduces maintenance costs. It will also provide the advantage to improve the quality, productivity and profitability of our production plants.

Predictive maintenance is an environmentally driven preventive maintenance plan. Instead of relying on the average life statistics in the industry or plant (for example:

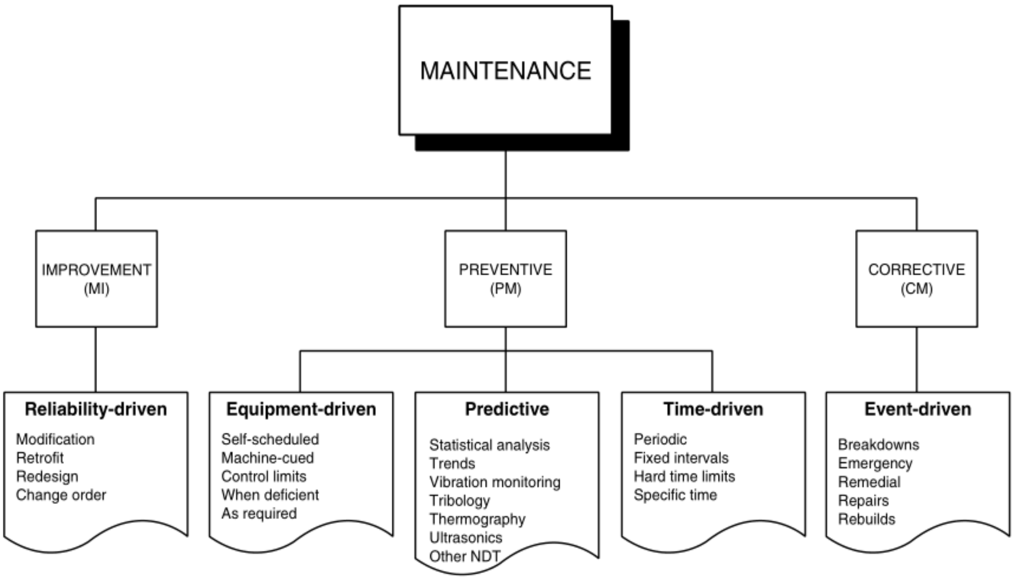
The mean time to failure) to plan maintenance activities, the forecast maintenance uses direct monitoring to determine the actual The mean time to failure(MTTF) or efficiency loss for each aircraft fleet and plant in the system and other indicators. At best, the traditional time-driven approach provides a normal guide to the life of the unit. Final decisions in preventing or running to failure based on repair or reconstruction plans must be based on intuition and the personal experience of the maintenance manager. The addition of a comprehensive predictive maintenance plan provides facts about the actual mechanical condition of each machine and operational data about the efficiency of each process system. This data is provided to the maintenance manager to use the actual data to schedule maintenance activities.

Predictive maintenance procedures minimize all unexpected failures of mechanical equipment in the plant and ensure acceptable mechanical conditions for maintenance equipment in the plant. The program can also identify machine trains before problems become serious. If the mechanical problem can be discovered and fixed early, most mechanical problems can be minimal. The degradation rate of normal mechanical failure modes is proportional to their severity. If the problem is in most cases, major repairs discovered early can be avoided. Simple vibration, fault analysis is based on two basic facts: all common fault modes have separate and identifiable components of different vibration frequencies and the amplitudes of each different vibration component will remain the same unless there is a change in the power of the machine train.

Predictive maintenance using process efficiency, heat loss, or other nondestructive technologies can quantify the operating efficiency of nonmechanical equipment or systems. These techniques used in conjunction with vibration analysis can provide the real information and condition of the plants to the maintenance manager or equipment engineer, which can them to optimal the reliability and availability of the machines and plants

3.1.4 The Type of Maintenance

From the figure, the maintenance can be divided into 3 type. They will be descripted as follow:



Fighre20 The structure of maintenance

1. The first type is improvement maintenance. We always focus on the maintenance, it's also necessary to pay attention to the source of the problem. Therefore, the purpose of improvement maintenance is to decrease or eliminate the need for maintenance.

   For example, many problems of equipment occurred at inboard bearings because of the environment problem, like damp, dirty and inaccessible location. Generally, the lubrication does not lubricate bearings that are inaccessible as often as he lubricates those that are easily accessible. Long life bearings with permanent lubrication can be considered to reduce lubrication requirements. If not, at least an automatic oiler can be installed. One of the main selling points of the new car is the elimination of ignition points that need to be replaced and adjusted, and the introduction of self-adjusting brake shoes and clutches that extend the oil change cycle.

2. The second type is corrective maintenance. Currently, most repairs are corrective. Maintenance is always needed. However, better improvement maintenance and preventive maintenance can reduce the need for urgent corrections. Clearly, a shaft which is broken is relatively easy to maintain because it involves few human decisions. Troubleshooting and troubleshooting fault detection and isolation are major time consuming aspects of maintenance. When problems become apparent, they can often be easily corrected. Intermittent failures and hidden defects are time consuming, but by diagnosing, you can isolate the cause and then correct it. From a preventive maintenance perspective, the problems and causes of failures provide the goal of eliminating failures through feasible preventive maintenance. The challenge is to detect the initial problems before they cause a complete failure and correct the defects as cheaply as possible. This leads us to three branches of preventive maintenance.

3. The final type is preventive maintenance. Preventive maintenance tasks are designed to prevent unplanned downtime and premature equipment failures that lead to corrective or maintenance activities. This maintenance management approach is primarily a time-driven planning or repetitive task, such as lubrication and adjustment, designed to maintain an acceptable level of reliability and availability.

3.2 The predictive maintenance of ball screw

3.2.1 The significance of maintenance of ball screw

The quality of ball screw in the feed system of CNC machine have important signification for the scientific and application. It is embodied in the following three aspects:

1. The ball screw play an important role to ensure the machining accuracy and quality. The assembly quality of the ball screw in the maintenance process of the feed system of the machine tool affects the machining performance and the quality of products. By evaluating the assembly quality of ball screw, measures are taken in advance to ensure the machining accuracy and quality of parts.

2. The second purpose is to reduce machine downtime and improve machine assembly efficiency and reduce machine maintenance costs. By testing the assembly quality of ball screw, it can find out whether there is any problem in the operation of the screw in time, and adjust in advance to reduce the downtime and reduce the maintenance cost of the machine tool.

3. It's can also improve the life time of ball screw. Before the ball screw is used, the machine tools with poor assembly condition of the ball screw can be found in time, and the service life of the ball screw can be improved by mechanical structure or servo parameter adjustment, so as to reduce parts replacement and property loss.

3.2.2 The technology of signal analysis

Signal processing technology is an important step in the process of assembly quality detection of ball screw to maintenance. Ball screw assembly quality in the process of maintenance detection problem of signal processing is essentially analyze the collected signals. after removing redundant information and noise, we are able to get the high correlation characteristic value with ball screw assembly situation. In order to fully extract the sensitive features contained in the signal and accurately reflect the performance state of the ball screw pair, a variety of feature extraction methods are selected to analyze the collected signals.

- The analysis base on the time domain

  Time domain analysis is one of the most common and basic signal analysis methods in signal processing. Through the amplitude change process of the analyzed signal waveform in the time domain, some characteristics of the signal are analyzed, so as to judge the change of the system tendency.

  The calculation process of time-domain characteristic values is relatively simple and its significance is intuitive. However, the characteristic values fluctuate greatly and the characteristic changes are unstable. When the trend of the system characteristic values is relatively small, the fluctuation of the characteristic values tends to cover up the change trend.

- The analysis based on frequency domain

  Frequency domain analysis focuses on the frequency distribution and variation rule of signal. When the performance of ball screw pair changes, the vibration frequency of signal often changes. Therefore, relevant eigenvalues are extracted in the frequency domain and combined with eigenvalues of time domain to analyze the change trend of system characteristics and evaluate the change degree of ball screw assembly quality. The characteristic values in frequency domain include amplitude spectrum, phase spectrum, power spectrum, power spectrum density, frequency variance and barycenter frequency.

Frequency domain analysis can obtain the periodic signal change of ball screw and the change trend of its own inherent characteristics, but frequency domain analysis cannot analyze the signal without stable frequency domain characteristics and the information of losing about local time. For this, more sensitive feature information can be obtained by time-frequency domain based feature analysis.

- The analysis based on time-frequency domain

The time-frequency analysis method combines some characteristics of time-domain analysis and frequency-domain analysis, and describes the change process of frequency distribution of signal with time. Wavelet transform is an effective tool for time - frequency analysis, which was put forward by a France Engineering named Morlet J. Wavelet transform has good time-frequency localization characteristics and can effectively deal with non-stationary random signals. Its research idea is to decompose the signals in the frequency domain continuously. Each group of signals contains only fixed frequency components and then reconstruct the signals with different frequency components.

Time-frequency analysis method that can be used to analysis stationary signal can also be used to analyze non-stationary random signal. It is widely applied to detecting state in key parts of machine tool. When the ball screw pair in the maintenance of the assembly in the process of situation changes, we can evaluate the ball screw assembly quality in the maintenance process through the time-frequency analysis. Therefore, when the characteristic values extracted by time domain analysis and frequency domain analysis cannot well reflect the state of the ball screw, time and frequency domain analysis can be used to decompose and reconstruct the signal, reduce the noise of the fault signal and extract effective information. But the application of the calculation is also relatively large.

- The analysis based on modal parameters

Due to mechanical structure of the modal parameters (natural frequencies, modal damping and modal vibration mode) is its physical characteristics (mass, damping, and stiffness) function and also the parameters of the dynamic characteristics of structure. The change of the structure often lead to change its physical properties, which affect the dynamic characteristics of structure. So through the study of the dynamic characteristic of ball screw test such as hammer experiment, the modal parameters of the ball screw changes to reflect the dynamic characteristic of ball screw. It is a feasible realization of ball screw assembly quality detection method in the process of maintenance. But due to the structure performance changes in modal parameters change is not very significant. Detection method based on modal parameters in the application of fault diagnosis and identification is relatively small and the accuracy of modal parameter identification and resolution affected by many other factors such as boundary conditions, the influence of the joint surface state and so on. It should not be used independently to detect the state of the structure components, need to be combined with other characteristics for identifying the multiple features fusion method.

3.2.3 The tools and method for the detect

CNC machine state inspection methods are divided into direct method and indirect method. Direct method is directly related to parts of precision, form and position tolerances of measurement, such as measured with a dial gauge between screw and guide rail parallelism and beating of screw itself, but this method of direct measurement precision is not high. Moreover, it’s also time-consuming, laborious and prone to staff the influence of operating level. The indirect detection method is to extract the characteristic information that can reflect the state of the relevant parts of the machine tool by detecting other signals during the operation of the machine tool.

Machine the fitting precision of ball screw drive system will affect the screw runtime friction torque, motor rotary encoder and the difference of grating ruler, screw parts related parameters, such as natural frequency and these parameters affect the current, vibration and the position error signal. So can detect signal data, extract characteristic information, to reflect the machine tool of the ball screw assembly quality.

In this paper, we focus in the indirect detection method which is adopted to detect the assembly status of ball screw, and the selection of the detected signal type is also the key link in the assembly quality detection research during the maintenance of ball screw. Acoustic emission signal is an instantaneous elastic wave generated by the rapid release of energy from local stress concentration source, which can be used to reflect the properties and stress distribution of materials. The laser measurement is based on the principle of comparing the absolute value of synchronous displacement. The Angle measurement is made by circular grating and the length measurement is made by laser measuring system. Current signal detection is to measure the assembly quality of ball screw by collecting the current signal of the motor which is related to the assembly condition of the machine feed system. In the selection of monitoring methods should be based on the advantages and disadvantages of each monitoring method, the actual situation of the industrial site, the cost of detection and the future engineering application. The advantages and disadvantages will be introduced at follow table.

Table 4 the advantages and disadvantages of each monitoring method

signal	advantages	disadvantages
Acoustic emission signal monitoring	The detection energy comes from the measured object itself, which is suitable for other methods that are difficult or unable to approach the environment.	High sampling frequency, large acquisition and processing cost, installation needs to design fixture. Weak signal and vulnerable to external interference.

Laser signal detection	High accuracy, high resolution, fast dynamic response, large measurement range and strong anti-interference ability.	The operation of measurement is complicated. The cost is high and the optical system needs to be kept clean, otherwise the measurement result will be affected.
Current signal monitoring	Convenient installation, low acquisition cost and the current is proportional to the driving torque, signal interference is relatively small.	The sensitivity of signal is low and it contains characteristic information of other components. There are many harmonic interferences, which need higher requirement of signal processing.
Vibration signal monitoring	The sensor is easy to install and has high sensitivity. The vibration information is directly related to the assembly of ball screw.	The signal is easily interfered by the outside world and on the same time the high sensitivity also puts forward a higher requirement for the location of the sensor.
Machine tool internal signal monitoring	Can directly obtain machine tool instantaneous speed, position, drive torque and other information. The reliable of signal is high. cost-effective.	The signal is far away from the fault source and suffers from large pollution. The information reflecting the fault is weak and the sampling frequency is low.

In the practical，For the application of those detect methods in the industrial field. The field environment, processing conditions and other factors should be considered to select the detection signal. Because there are hundreds of machine tools in workshop to work at the same time, lead to the scene of the environment is very noisy, interference is larger, the noise interference of acoustic emission sensor sensitivity is reduced. And the installation of acoustic emission sensor need special fixture, even may also need to change the machine structure, which will impact on machine tool processing. Therefore, it is not suitable. Moreover, as the research target, the ball screw is located in the CNC machine tool, which can be used to install the sensor in a small space. During processing, the chip, cutting fluid and other conditions make the site harsh, which brings inconvenience to the laser signal detection. The current sensor is convenient to install and the current signal is simple to collect, which has no impact on the machine tool running process. Moreover, the current signal can reflect the wear state information of the machine tool, which is easy to realize the later engineering application. Therefore, the current signal can be used as one of the methods of assembly quality detection in the maintenance process of ball screw. Although the vibration and noise in the workshop are very large, the floor specially made in the workshop and the base of the machine have the function of buffering and isolating vibration. After selecting the appropriate installation position, the vibration sensor can also truly reflect the vibration of the ball screw.

3.3 The maintenance of ball screw based on feed motor current

Although the current signal contains fault information, it also contains a lot of noise information. Wavelet theory is a new time-frequency analysis method, which can realize the reasonable separation of signals at different time and frequency bands, eliminate the noise information, reconstruct a clearer signal characteristic graph and improve the definition of signals. Generally, the analysis of time domain used to be adopted to analysis the current signal. There are 4 factor that need to be considered. The variance eigenvalue can represent the size of the fluctuation component in the current signal. For example, the assembly problem of the ball screw will cause the fluctuation of the machine tool, which will be reflected in the signal. Therefore, the assembly quality of the ball screw can be reflected by the variance eigenvalue. The sum of squares and eigenvalues can represent the amount of energy in the current signal. For example, when the lead screw tilts, it can be known from the previous analysis that the friction torque of the transmission system will increase, which will lead to the increase in the energy of the current signal. Therefore, the tilt of the ball screw can be reflected by the sum of squares and eigenvalues. Root-mean-square value is an important characteristic value representing non-stationary signals, which not only contains the change information of stationary signals, but also can represent the fluctuation degree of non-stationary signals. Kurtosis factor and margin factor eigenvalues are dimensionless parameters, which have advantages over kurtosis and margin eigenvalues. The characteristic value of kurtosis factor is sensitive to the impact phenomenon of abnormal pulse. When the assembly situation of ball screw changes, its contact stiffness, friction torque and other parameters may change, which can lead to the impact phenomenon. Therefore, the impact situation of ball screw can be reflected by the characteristic value of kurtosis. The characteristic value of margin factor is the peak value of signal divided by the root mean square value, which is an important characteristic value representing non-stationary signals. It not only contains the change information of stationary signals, but also can represent the fluctuation degree of non-stationary signals.

3.3.1 The theory of current signal

The motor driving ball screw pair is three-phase ac asynchronous servo motor. The current signal has the characteristics of easy acquisition of sensor and low acquisition cost, so the current signal is widely used in the field of state monitoring. The relationship between servo motor three-phase current signal and the assembly quality of ball screw will be analyzed below.

According to the electromagnetic theory of the motor, the calculation formula of the output torque of the servo motor is:

$$\mathrm{T}=K_T \emptyset I_1 \cos\varphi$$

From the equation above, T is motor electromagnetic torque, K_T is the motor structure factor, $\emptyset$ is unipolar magnetic flux for motor rotating magnetic field, I_1 is the rotor current, $\cos\varphi$ is the rotor winding circuit power factor.

$$I_1 = \frac{E_1}{\sqrt{X_L^2 + R^2}} = \frac{sE_0}{\sqrt{(sX_0)^2 + R^2}}$$

$$\cos\varphi = \frac{R}{\sqrt{R^2 + (sX_0)^2}}$$

For the above equation, s is the slip of the driven motor, R is the resistance of the rotor winding, X_L for rotor winding leakage inductance, U_1 power supply voltage for the motor.

When the applied voltage and frequency of the servo motor remain constant, the motor torque is:

$$T \approx K\frac{sR}{R^2 + (sX_0)^2} * U_1^2 = K\frac{sR^2}{R^2 + (sX_0)^2} * I^2$$

K is a constant and I is the stator current.

From the equation, the output torque of the servo motor is related to the stator current and slip of the motor. If the slip of the servo motor remains unchanged, the output torque of the servo motor is only related to the current. Therefore, the mapping relationship between current and the output torque of the motor can be established. When the machine is idle and the table is fed at a constant speed along the X direction, the driving torque of the servo motor is equal to the friction torque of the feeding system and then the variation trend of the friction torque of the ball screw can be reflected by the current signal.

3.3.2 The equipment for the current signal

3.3.2.1 current sensor

We use hall current sensor collects current signal of ball screw. Hall current sensor based on the magnetic balanced hall principle, and the closed-loop principle. When the magnetic produced by the original edge of current IP through the magnetic circuit that formed by the high quality magnetic core. Hall elements are fixed in the air gap to detect magnetic flux. By means of the number of turns around the magnetic core coil output reverse compensation current, the reverse compensation is used to offset magnetic produced by the original edge of current IP, resulted in the zero flux always stay in the magnetic circuit. After special circuit processing, the output end of the sensor can accurately reflect the current change of the original side current.

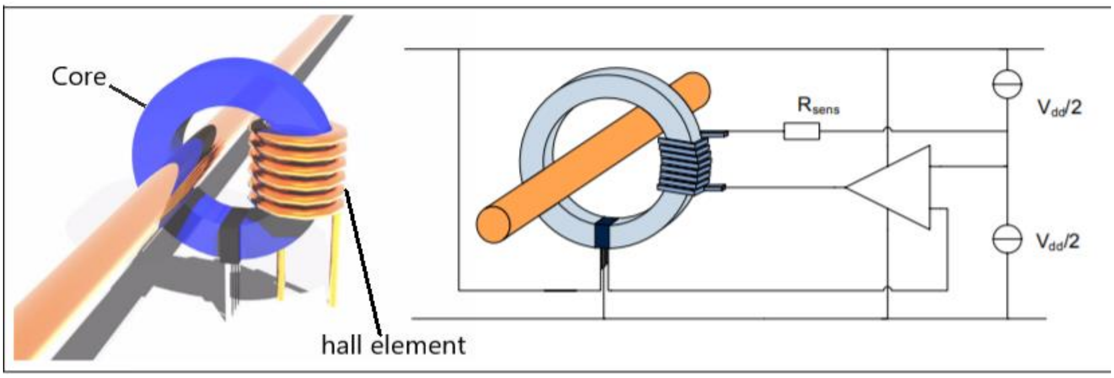


Figure21 The hall current sensor

3.3.2.2 The mechanism of the preload adjustment

Based on the modified double nut structure, the design idea of preload adjustable mechanism of feed drive system is put forward. The preload adjustment mechanism is established by adjusting the force between the master nut and the slave nut. This is done by rotating the precise positioning screw nut. Install a disc spring between the screw nut and the flange and fix the slave ball nut on the flange. When the precise positioning nut rotates the compression disc spring, the applied force increases the space between the master and slave nuts, thus squeezing the ball in the master and slave nuts. Therefore, the ball screw on the preload force. In the construction of preload adjustable mechanism, select the size of the ball in the master nut and the slave nut, so that the applied preload force remains at zero or so. Then we can adjust the preload by compressing the disc spring. According to the compression of the disc spring and the data sheet of the spring, the applied preload can be evaluated.

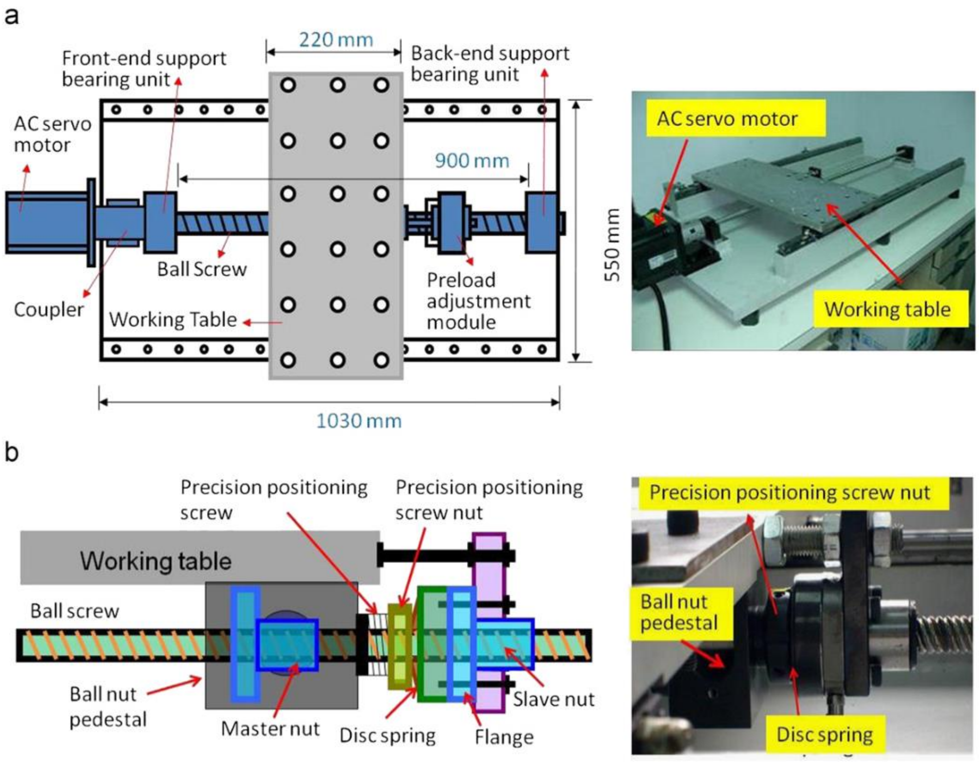
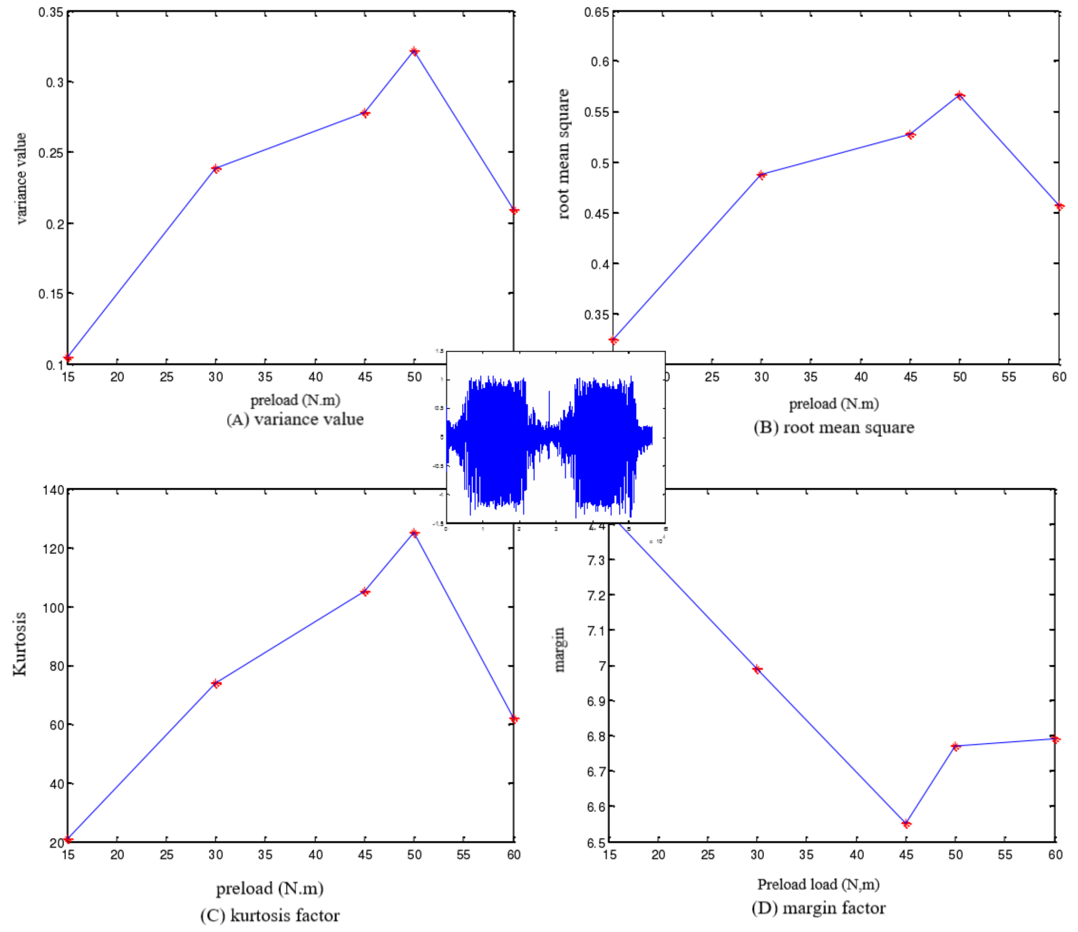


Figure22 (a) Configuration of the single-axis experimental feed drive system with a preload-adjustable module. (b) Illustration of the designed preload-adjustable module constructed with a disk spring based force tunable mechanism between the master and the slave nuts.

In order to achieve the preload adjustable structure on the feed drive system, the work table is fixed on the master nut by the ball nut seat. The slave nut is connected to the master nut by a preload adjustable mechanism, which also includes a support column structure (bolt screw) directly above the ball screw shaft. The reason are descripted as follow. Due to the weight of the table, the ball screw shaft may cause slight deflection. However, the relatively large gap between the master and the slave nuts (compared with the commercial double nut structure), for easily manipulating the disk spring in our design, might create an extra bending effect caused by the section of the ball screw shaft between the master and the slave nuts compared to the normal double nut ball screw motion. Therefore, the column supporting structure is used to minimize this possible bending effect.

3.3.3 The analysis of results

During experiment, the locking nut at the screw bearing is adjusted. The trend of characteristic values in each time domain with the increase of bearing preload torque is analyzed. The preloading torque of the bearing during the experiment is [11] 15N·m, 30N·m, 45N·m, 50N·m, 60N·m in sequence, and the preloading torque position of the bearing in the standard ball screw assembly process is455N·m. The time domain characteristic values analyzed are variance, root mean square, kurtosis factor and margin factor.



(A) variance value

(B) root mean square

(C) kurtosis factor

(D) margin factor

Figure23 The time-domain characteristic trend of bearing preloading torque variation of 2000mm/min

Figure23, shows the change trend of characteristic values in each time domain along with the bearing preloading torque after the wavelet packet filtering of RMS value of X-axis three-phase current in the circular track movement with feed speed of 2000mm/min [11]. Figure (A), (B), (C), (D) shows the four time domain characteristic values of variance, root mean square, kurtosis factor and margin factor respectively. With the increase of the preload torque of the screw bearing, the characteristic values of variance, root mean square and kurtosis tend to increase first and then decrease. The characteristic values of margin factor tend to decrease first and then increase. This is because as the preload torque of the screw bearing increases, the friction torque of the bearing also increases when it rotates. And ball screw axial positioning and fixed on machine tools rely mainly on bearing locking bolt and nut locking bolt, when bearing preload torque is too large, ball screw in the axis to the degrees of freedom is reduced, which reduced the lead screw axial channeling dynamic range. Thus, reducing the impact of the ball in and out of the reverser produce friction torque. So the friction torque of the bearing still increases as it rotates. However, the total friction torque of the feed system is decreasing. Therefore, with the increase of bearing preload torque, the friction torque of the transmission system shows a change trend of first increasing and then decreasing. There is a positive proportional relationship between the friction torque of the feed system and the motor's three-phase current signal. So the characteristic values which extracted from the RMS values signal of the X-axis three-phase current also show a change trend of first increasing and then decreasing. The characteristic parameters have a maximum value when the preload torque is between 45N·m and 50N·m. While the preload torque in the standard assembly process is 45N·m. Therefore, the characteristics of the circular track moving current signal can be used as an index to evaluate the assembly quality of ball screw.

When the bearing preloading torque is too small, the axial stiffness of the screw decreases, while when the bearing preloading torque is too large, the friction torque will also increase. When the preloading torque is 45N·m and compared with 15N·m, the variance eigenvalue of the X-axis three-phase current RMS value increases by 256% and the RMS eigenvalue increases by 163% in the circular track movement with the feeding speed of 2000mm/min. The characteristic value of kurtosis factor increased by 500%. The characteristic value of margin factor decreased by 13.4%.

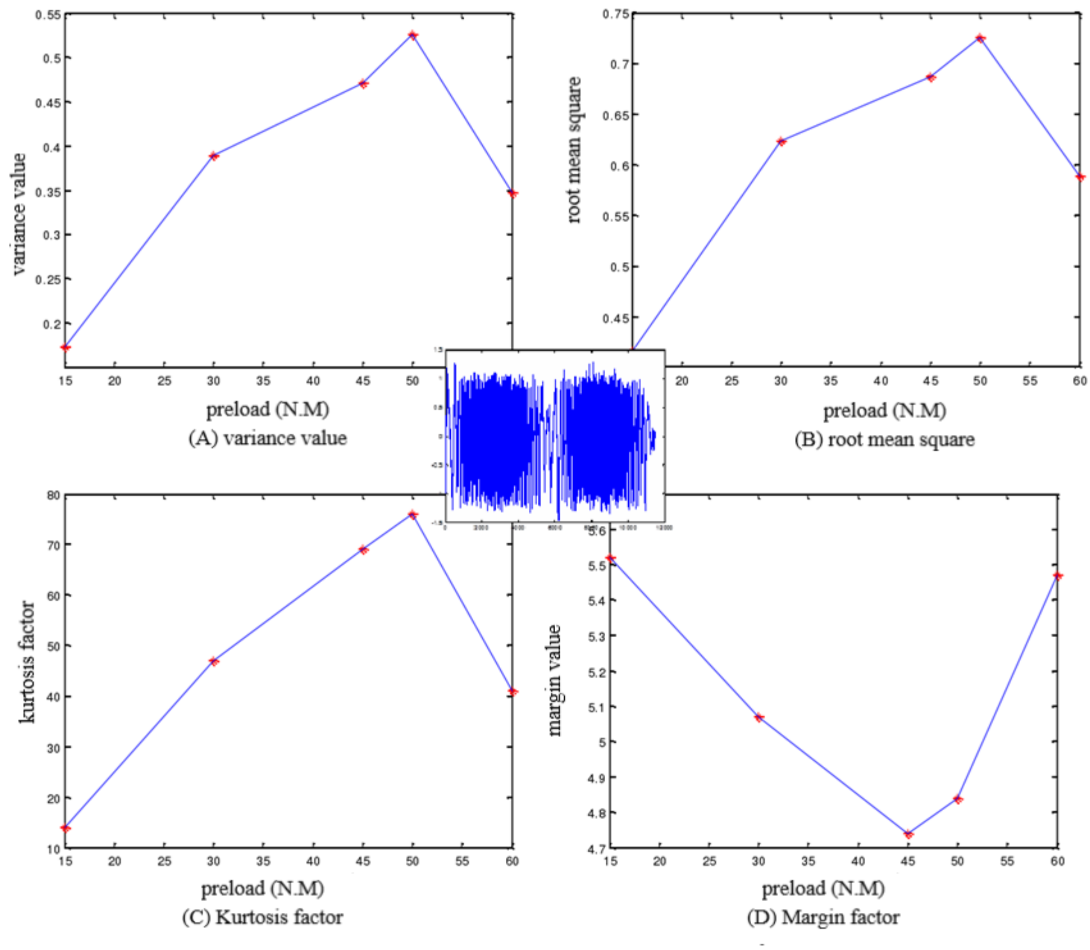


Figure24 The time-domain characteristic trend of bearing preloading torque variation of 10000mm/min

Figure24, shows the change trend of characteristic values in each time domain along with the bearing preloading torque after the wavelet packet filtering of RMS value of X-axis three-phase current in the circular track movement with feed speed of 10000mm/min. Figure (A), (B), (C), (D) shows the four time domain characteristic values of variance, root mean square, kurtosis factor and margin factor respectively.

When the preload torque is 45N·m, compared with 15N·m, the variance eigenvalue of the X-axis three-phase current RMS value increases by 273% and the root-mean-square eigenvalue increases by 165% in the circular track movement with the feeding speed of 10000mm/min. The characteristic value of kurtosis factor increased 493%. Margin factor eigenvalue decreases by 16.5%.

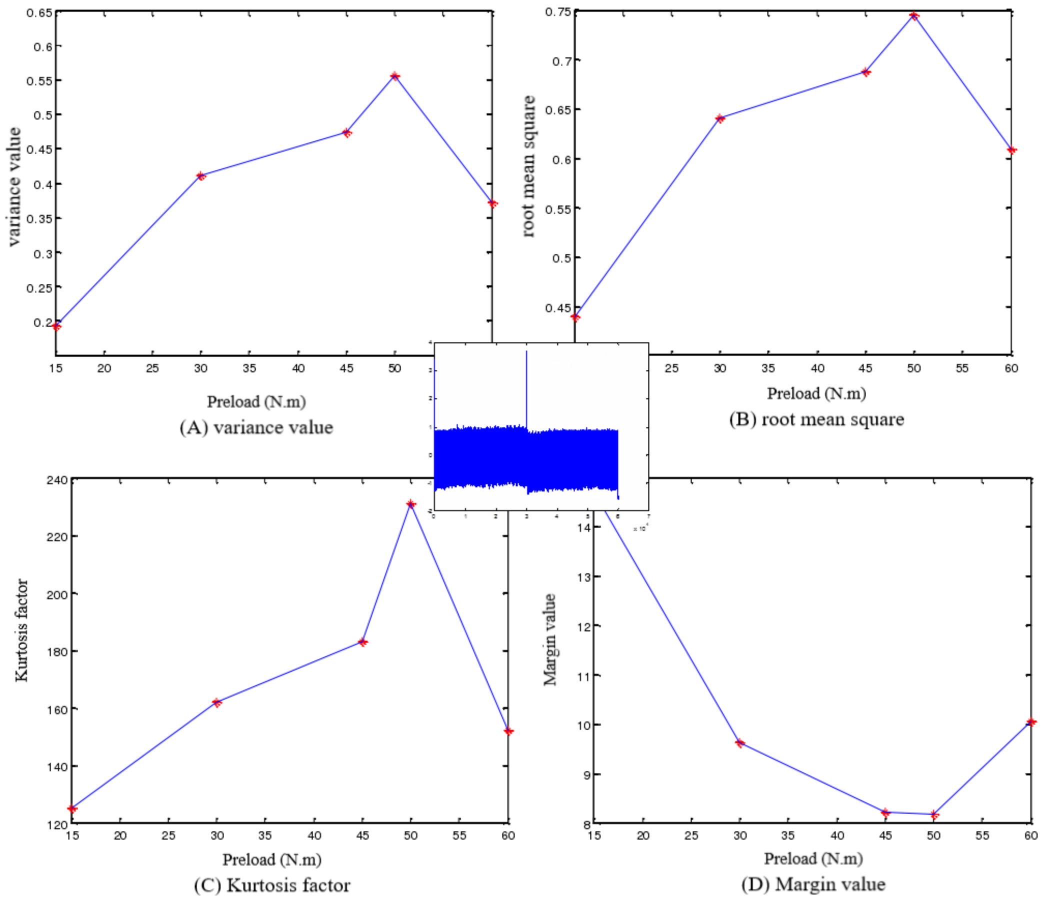


Figure25 The time-domain characteristic trend of bearing preloading torque variation of 2000mm/min of linear motion

Figure25, shows the change trend of characteristic values in each time domain along with the bearing preloading torque after the wavelet packet filtering of RMS value of X-axis three-phase current in the linear movement with feed speed of 2000mm/min. Figure (A), (B), (C), (D) shows the four time domain characteristic values of variance, root mean square, kurtosis factor and margin factor respectively. When the preload torque is 45N·m, compared with 15N·m, the variance eigenvalue of the X-axis three-phase current RMS value increases by 246% and the root-mean-square eigenvalue increases by 156% in the linear movement with the feeding speed of 2000mm/min. The characteristic value of kurtosis factor increased 146%. Margin factor eigenvalue decreases by 78.9%.

Compare those 3 picture, it can be found that the variance, root mean-square, kurtosis factor and margin factor of the four time domain characteristic values have roughly the same change trend under the current signal of different movement modes. And the variance, root mean-square and kurtosis factor have basically the same change trend under the same current signal. By comparing the change amplitude of different characteristic values, it can be found that the variance and kurtosis factor of the X-axis three-phase current RMS value in the circular track movement with the feeding speed of 10000mm/min have relatively large changes, with the characteristic value of variance increasing by 273% and the characteristic value of kurtosis factor increasing by 493%. Therefore, the variance and kurtosis factor characteristics of the circular track motion current signal of the feed speed of 10000mm/min can be considered as one of the indexes to evaluate the assembly quality of the ball screw.

3.4 The maintenance of ball screw based on vibration signal

3.4.1 The application of vibration signal

It may be more realistic to consider the structure formed by the master nut, slave nut and bench as a continuum body. During the motor torque applied to the ball screw, the vibration of the ball screw is transmitted to the continuum body through the ball in the ball nut. Therefore, the ball in the ball nut can be regarded as the medium of vibration source. Stronger vibration signals can be detected at the location of the medium closer to the vibration source.

When we compare the signal levels (or spectrum amplitudes) detected at three different locations (master nut, slave nut, and bench), the sensor position on the bench is further away from the ball than the sensor position. Two nuts, so the minimum signal level is obtained. The scheme of sensing the vibration of the main nut USES embedded sensor technology. The manufactured PCB chip with the accelerometer is mounted in a small metal tube, and the detection unit with the shell is embedded in the machining chamber of the ball nut base. The estimated distance between the surface of the master nut and the accelerometer is approximately 6 mm.

On the other hand, the PCB chip made with the accelerometer sticks directly to the surface of the slave ball nut. Therefore, higher signal levels can be obtained. Therefore, the magnitudes of the detected signals from the slave nut are slightly greater than those from the master nut, and the strength of the signal from the working table was much lower than from both ball nuts.

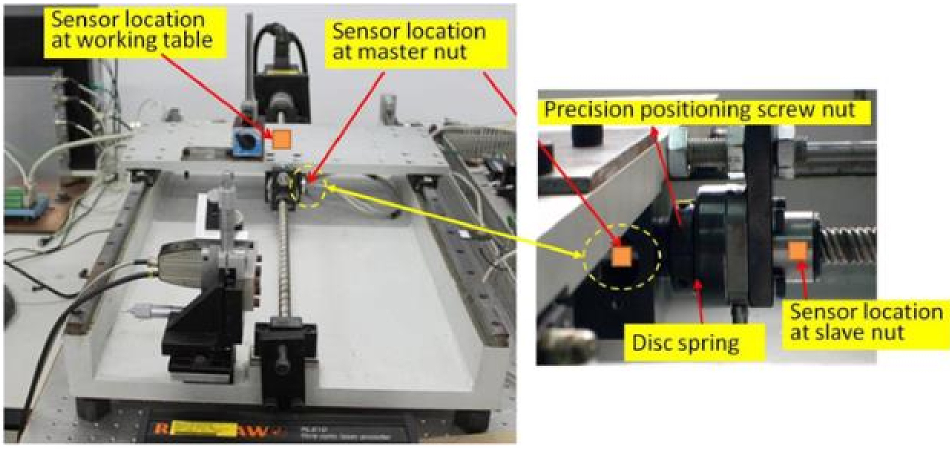


Figure26 Vibration measured locations at the master nut, the slave nut, and the working table.

3.4.2 The sensor system of vibration signal

It's necessary to design a cost effective and precise sensor system for the vibration signals for monitoring the condition of ball screw. We use commercial available MEMS accelerometer for sensing vibration. This electrostatic drive sensor works as follows. The change of capacitance in the comb drive structure of the accelerometer will change the output voltage, which is related to the change of acceleration.

This sensor can monitor the two-axial accelerations simultaneously, with a bandwidth of [12] 2.5 kHz and maximum detectable acceleration of ± 18g. Due to its lead frame chip scale package (LPCSP) package, the size of the packaged accelerometer is only 4 mm × 4 mm × 1.45 mm [12]. Therefore, it is not easy to build the prototype sensing unit by integrating the device into the PCB chip. We used micromachining technology to make patterned SU-8 chips so that solder paste can be selectively applied to the PCB chip to fix the accelerometer and connect the sensing signal to the pad on the

PCB chip. From Fig.27, we can see the accelerometer on the circuit board.

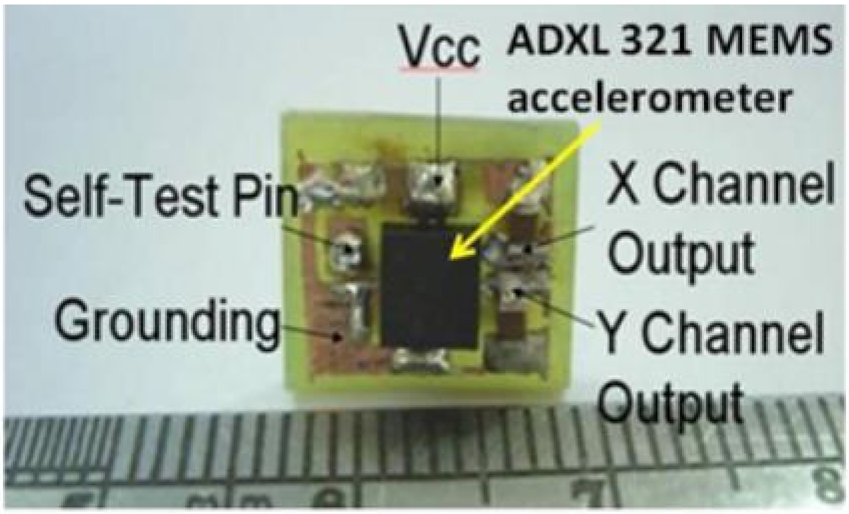


Figure27 Photo of the core sensing elements implemented on a 1 cm x 1cm PCB chip

Chapter4: Conclusions

This paper introduce the type of the failure of the ball screw and the cause of the error. The friction, preload, assemble accuracy, environment and the condition of lubrication is the main reason for the failure of ball screw. Thus, maintenance is important for the improvement of the efficiency of CNC machine, which can decrease the cost of production. The development of maintenance experience 5 stage: breakdown maintenance, prevention maintenance, productive maintenance, total productive maintenance and predictive maintenance. There are many detect method for the maintenance, etc. acoustic emission signal, current signal, laser signal, vibration signal and Machine tool internal signal. Because there are hundreds of machine tools in workshop to work at the same time, lead to the scene of the environment is very noisy, interference is larger, the noise interference of acoustic emission sensor sensitivity is reduced. And the installation of acoustic emission sensor need special fixture, even may also need to change the machine structure, which will impact on machine tool processing. Therefore, The current signal and the vibration signal much more useful for the monitor of the condition of the ball screw.

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