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Structure Design of Positioning Device Based on Mechatronics

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In order to study the positioning device structure based on mechanical design technology, PLC technology and sensor technology, the structure of the positioning device is analyzed mainly from the structure design. Firstly, the overall scheme of the positioning system is designed, and then the theoretical analysis and modeling of the ball screw pair are carried out. The results show that the contact stress between ball and screw raceway is larger than the contact stress between ball and nut, and the contact factor should be considered in the design of lead screw pair. The contact force between ball and nut, ball and screw is most obviously affected by speed. DN value and contact angle affect contact velocity indirectly. Finally, according to the simulation results and the theoretical calculation, the mechanical structure design of the mechatronics precise positioning device is determined.

1. Introduction

With the combination of mechanical technology, information technology and electronic technology, mechatronics technology has become a new technology to achieve the overall optimization of the production process and industrial products. In order to realize the needs of the development of high and new technology, remote control unmanned system is bound to become an inevitable trend of development and a new research field, and it is very popular (Sung et al., 2017).
Based on mechanical design technology, PLC technology, sensor technology, automatic control technology and digital control technology and other multidisciplinary theories and technologies, a set of complete mechatronic precise positioning device is designed. The device integrates power, machinery and control technology, including transmission and drive part, information processing, detection part and power supply part, as well as control part. There are three kinds of interfaces: mechanical interface, signal interface and power interface. Through three kinds of interfaces, the upper computer can control the lower computer and the positioning device. The mechatronic precise positioning device and control system technology can be applied to the field of micro assembly, micro machinery, and it can also be applied to electronic information industry, precision measurement, ultra-precision machining, semiconductor lithography, biological cells and nanotechnology fields.

2. Overall scheme

The overall configuration of the positioning system is shown in figure 1. The basic structure of the positioning system consists of the following aspects
Stepper motor and controller: drive ball screw;
Ball screw: converts the screw drive into linear motion to drive the nut and its accessories movement;
Nut: it will locate the components to install the foundation and drive the middle bridge;
Servo motor and controller: it can drive positioning parts to achieve position torque control;
PLC: it sends out pulses to control stepping motors and servo motors;
HMI man-machine interface: it will display and detect the working state in real time.

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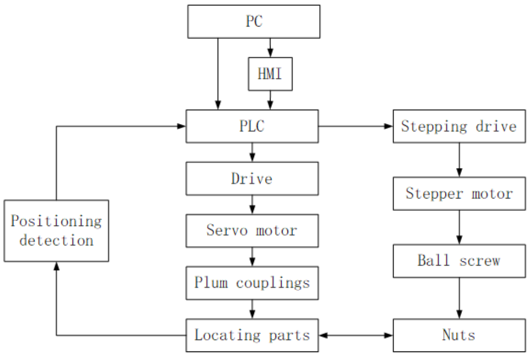

Figure 1: The composition of the device

3. Simulation study of ball screw

3.1 Structure diagram of ball screw

Because the design involves accurate transmission, the ball screw is the key part of the design. Therefore, it is especially important to improve the accuracy of ball screw transmission. Figure 2 is the working principle diagram of the ball screw pair. The basic components of the ball screw include: screw, nut, ball, reverse.

The working principle of ball screw: The screw 1 rotates under the rotation of the rotating mechanism or the motor, and the ball 4 is pushed along the spiral raceway to roll in the closed loop. At this point, if the nut is limited to rotate, the nut 2 moves linearly with the ball 4. Under the action of the return device 3, the ball 4 moves along the raceway and automatically returns to the entrance of the work through the channel, so that the ball can be recycled on the threaded raceway. On the other hand, if the nut moves in a straight line and the axial movement of the screw is limited, the screw will do the rotary motion under the interaction of the ball and the screw as well as the nut, which is usually called inverse drive.

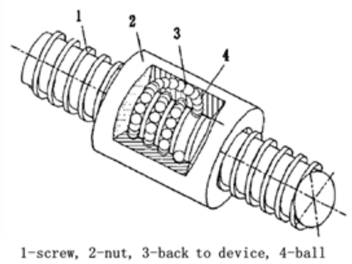

Figure 2: The schematic diagram of ball screw

3.2 Dynamic modeling and analysis of ball screw pair based on virtual prototype

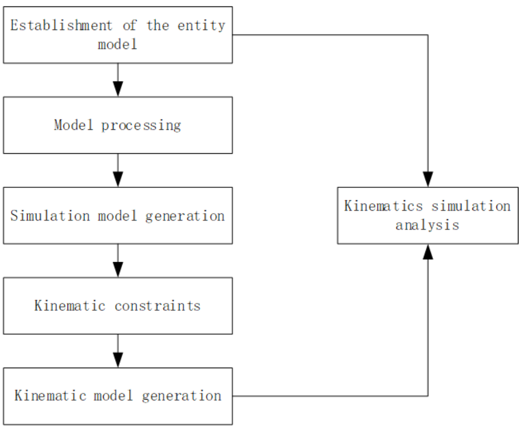

Figure 3: The simulation analysis procedure of ADAMS

Assembly model of single nut single roll in 3D Software Solidworks, and introduced into the dynamic analysis software ADAMS. Contact should be added between ball and nut, screw and reverse device. The reverser, nut and screw are connected by a defined moving pair. The screw and the ground are connected by hinges. The simulation can be done after the motion, the simulation time and step size are set.

Contact is the main constraint in the structure of ball screw, which includes contact between ball and nut, ball and screw, ball and ball, ball and reverse (Aram et al., 2017). Contact can be used to define the contact model in ADAMS. It uses the following 4 inequalities and equality equations to represent contact constraints:

$$
\begin{aligned}
& g \geqslant 0 \\
& Fn \geqslant 0 \\
& Fn \bullet g \bullet g = 0 \\
& Fn \bullet g \bullet \frac{dg}{dt} = 0
\end{aligned}
\tag{1}
$$

In the formula, g--the penetration depth connected the two constructs. The positive value means that the two are penetrating each other. Fn--normal contact force. Its cross is non-negative value. $\frac{dg}{dt}$--the mutual penetration velocity of two components.

The first three expressions above represent in turn: The first expression represents the constraint condition that no penetration occurs between the components. The second expression represents the constraint condition that the contact normal force is greater than zero and the constraint condition that the contact force is not zero when the contact occurs. However, the last expression is called the continuity condition, which means the condition that the contact force is not zero when the penetration velocity is zero. There are two models in ADAMS to calculate normal contact force: recovery coefficient model and impact function model. Based on the impulse theory, the recovery coefficient model is not suitable for the continuous contact problem, so the impact function model is adopted. The contact force is defined by velocity and displacement in the impact function model, which can be used in continuous contact. Moreover, the stiffness k is related to the material properties, and the physical meaning is obvious. When the larger rigidity is selected, it is easy to cause the convergence difficulties. Under this condition, the depth of penetration can be adjusted to improve convergence, and its calculation is relatively stable. The model of impact function in ADAMS is expressed by a spring damping model. The impact function is shown in formula (2):

$$
Fn = k \quad g \quad g^{e} + STEP(g,0,0,d_{\max},c_{\max}) \quad g \quad \frac{dg}{dt} \tag{2}
$$

In the formula, k-- spring stiffness; e—shape index, decisive force- shape of displacement relation curve. According to Hertz theory, when the two members of the contact are all steel materials, then e=1.5. STEP ()—lump function. These expressions can be referenced to the ADAMS user manual. dmax--Maximum allowable penetration depth. cmax--Maximum damping value when reaching the maximum penetration depth. It represents the loss of energy when the component collides, and the value is generally 0.1%-1% of the stiffness value (Ninita et al. , 2017).

As shown in figure 4, the relationship between the contact force and time between ball and screw, ball and nut, ball and ball is obtained by dynamic simulation.

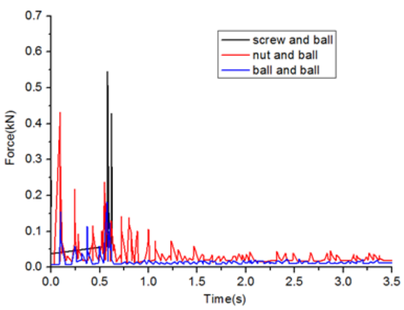

Figure 4: Contact force varying with time

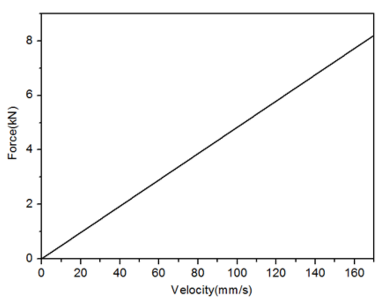

Figure 5: The relationship between contact force and the velocity

The analysis results show that the contact force between the nut raceway and the ball is less than the contact force between the screw raceway and the ball. The contact stress of the nut raceway is smaller than the contact stress between the ball and the lead screw raceway (Lisa et al., 2017). The difference of contact stress is sure to lead to the difference of friction characteristics. The contact stress between the lead screw raceway and the ball is larger. Therefore, the friction is large, and the wear is fast, which is consistent with the actual results. Figure 5 is the relation curve of contact force with speed.
As shown in the figure, the contact force increases with the increase of velocity, and the impact of impact velocity on the contact force reaches the linear. The speed of the screw N and the nominal diameter D of the ball screw pair are usually used to express the speed characteristics of the screw pair, which is called the DN value. The DN value actually reflects the speed of the ball.

4. Mechanical structure design of mechatronic precise positioning device

There are many kinds of positioning devices for precise engineering because of their different working characteristics and uses. There are one-dimensional, two-dimensional or multi-dimensional motion, and these different device is combined based on the one-dimensional motion. In order to realize the large stroke motion and high speed accurate motion of the positioning device, one dimensional large stroke motion control technology is the key. On the basis of the first stage positioning control, the micro positioning control is superimposed (Jia et al., 2017). Therefore, the first stage positioning is the basic component of the precise positioning system, which has a very important impact on the positioning accuracy.

4.1 Design of screw for positioning device

Main specifications and technical parameters of the device
Working stroke: 300mm;
Fast feed speed: 10m/min;
Gross weight on feed system: 15kg;
Positioning accuracy: 0.016mm;
Repeatability positioning accuracy: 0.007mm.
Load of ball screw pair
The minimum load Fmm is the axial force acting on the ball screw pair when the device is unloaded, such as the friction caused by the positioning weight. The friction force caused by the gravity of the supporting frame is Fmm.

$$F_{mm} = umg\cos\theta + umg\sin\theta = 0.62N \tag{3}$$

The maximum load Fmax is the maximum axial load that the screw pair may bear, and the maximum axial load is 60N.
The equivalent load Fm and the equivalent speed nm vary with the working load. If the working load is proportional to the speed and the speed is equal, the equivalent load Fm and the equivalent speed nm can be calculated by the following method formula:

$$F_m = \frac{2F_{\max} + F_{\min}}{3} \tag{4}$$

$$n_m = \frac{n_{\max} + F_{\min}}{2}$$

The minimum speed can be neglected through the analysis: Fm=40N, nm=2000r/min。
Main parameters of ball screw pair
Lead Ph $P_h = \frac{V_{max}}{in_{max}}$: Vmax is the fastest speed of positioning (m/min), Vmax=10m/min. nmax is the maximum speed of drive motor (r/min), nmax=3000r/min. i is the transmission ratio, i=n screw /n motor. The motor is directly connected with the screw, i=l. Ph=10/3000≈4(mm) is calculated.
Bottom diameter of ball screw d2m: The system stiffness K varies with the position of moving parts in the mechanical transmission device. Kmin means the minimum stiffness. Once the screw pairs appear to working load, the transmission system will produce elastic deformation δ, and δ=F/K. Therefore, the transmission accuracy of the system is affected, and Kmin point is most affected.
The accuracy of servo system of mechanical equipment is mostly checked under no-load condition. The static friction force F0 is the maximum axial load on the ball screw pair under no-load condition. At Kmin, when the moving parts start and return, 2F0/Kmin (also known as friction dead zone error) will occur due to the change

of F0 direction. It is the main factor affecting the repetitive positioning accuracy, generally accounted for the repeatability of 1/2-1/3.

The ball screw pair is the core component. The most important factor affecting the positioning accuracy is its accuracy. Secondly, the elastic deformation of the ball screw itself (the elastic deformation varies with the position of the ball nut on the ball screw) and the variation of the friction torque of the ball screw pair are the other factors. The positioning accuracy of δm≤(1/4-1/5) is estimated. The small values estimated by the above two methods are taken as δm(um).

The positioning accuracy is 0.016mm, and the repeatability positioning accuracy is 0.007mm. Therefore, the maximum axial deformation is calculated and δm=1.75um is taken according to the minimum principle. The screw bottom diameter d2m of the ball screw pair can be calculated:

$$d_{2m} \geqslant 10\sqrt{\frac{10F_0L}{\pi\delta_m E}} = 0.039 \tag{5}$$

In the formula, E is the Young modulus. The maximum allowable axial deformation of ball screw is estimated as δm(um). F0 is the friction force (N). The distance between two fixed supports is (mm)L≈safe travel+travel+1 bearing length+Nut length+2 tail travel≈(1.1-1.2) travel+(10-14) Ph.

Length of screw thread of ball screw LS: LS is the sum of effective travel location (mm), tail travel (mm), nut length (mm).

The supporting mode, preload form and supporting bearing of ball screw pair are determined. Because the accuracy of the ball screw is relatively high, the supporting way with two ends fixed is the best choice due to its high rigidity. The ball screw is supported by angular contact ball bearing because of its large rigidity and small torque (Ana et al., 2017).

4.2 Design of coupling for positioning device

The coupling realizes the connection and separation of shaft, and realizes the transmission and interruption of force. But it has many kinds, and it can be divided into rigid couplings and flexible couplings according to their properties. Because of the special design of the structure, the flexible coupling has many functions. The functions of various couplings are as follows:

It can compensate the axial displacement, angular displacement and radial displacement of the two shafts due to the installation and manufacturing errors, and avoid excessive additional loads at the shaft ends;

It can relax the torsional impact on the shaft at work;

It can change the resonance speed of shafting. For example, when the shock absorption work is simultaneous. The torque angle will become larger. The smaller the impact torque is, the lower the resonance speed is. In addition, the moment of inertia of the coupling also affects the speed of the shaft.

It can reduce the torsional vibration of shaft.

Compared with other couplings, the quincunx shaped elastic coupling has the following characteristics:

The work is stable and reliable, and has good shock absorption, buffering and electrical insulation performance;

It has the advantages of simple structure, small radial size, light weight and small moment of inertia. It is suitable for medium and high-speed application.

It has larger axial, radial and angular compensation capabilities.

It has long service life and large carrying capacity. Safe and reliable polyurethane elastomer with high strength is abrasion resistant and oil resistant.

It doesn't need lubrication, so it has less maintenance and can run continuously for a long time.

In the precision transmission, the coupling is also the key part. As the basic component of the precise positioning system, macro positioning has a considerable impact on the positioning accuracy. The mechanical part composes of a driving part and a transmission part. Both the driving part and the transmission part have many types, but they have own advantages and disadvantages. The type of driving part has brushless DC motor, stepping motor, servo motor.

4.3 Design of the general assembly

The general assembly of positioning device is shown in figure 6. Its working process is like this: When the stepping motor turns on the power, it drives the screw pair to rotate and the nut drives the worktable movement under the action of the coupling. Precise positioning is achieved by controlling servo motor.

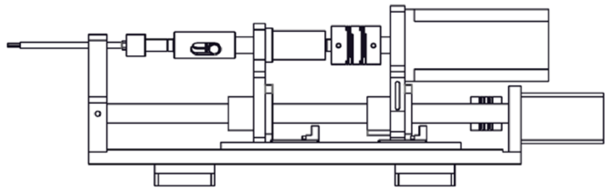

Figure 6: The assembly drawing

5. Conclusion

Taking the unmanned control system as the application background, the research of a mechatronics precise positioning device and its control system which has an independent function is promoted. The structure of the positioning device is designed, including the design of ball screw pair, coupling and so on, and the assembly diagram of the system is drawn. The results show that there is a great difference between the ball and nut, ball and screw contact stress. The contact stress between ball and screw raceway is larger than the contact stress between ball and nut of ball screw. One of the important reasons for the rapid wear of the lead screw raceway is that the different contact stresses lead to different wear characteristics of the two, which results in fast wear of the lead screw raceway, and affects the effective life of the screw pair. At the same time, the contact force is most affected by the speed, and the DN value and contact angle have an indirect influence on the contact speed.

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