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Analysis of CNC machine tool self-circulating hydraulic balance system

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Abstract: *In the field of industrial manufacturing, as an essential unit in CNC machining, balance of hydraulic system plays an influential role in precision machining. In order to reduce the pressing deformation of the workpiece and additionally improve the machining accuracy, this paper improves the self-circulation hydraulic balance system, and integrates the fluctuation rate and additional variables into the system parameter system, considers the variable relationship in the numerical control machine tool as a whole, and obtains the parameter calculation relationship. The simulation analysis proves that this model has a certain practical effect. It provides theoretical support for the further development of CNC machine tools.*

Keywords: *CNC machine tool; Self circulating hydraulic balance system; Precision machining*

1. CNC machine tool hydraulic system

1.1 The important role of hydraulic system for CNC machine tool

Hydraulic technology is an essential technology to ensure the transmission and control of CNC machine tools. Depending on the actual operation, the hydraulic transmission system mainly plays the following auxiliary functions in the application process of CNC machine tools. First, automatic tool-shifting actions are implemented, such as the unfolding, rotation, and swinging of the manipulator, as well as the basic actions of the tool. Second, it can ensure the overall balance of the moving parts of the CNC machine tool, such as the application of the hydraulic system, which can ensure the balance of the gravity of the spindle box of the CNC machine tool. Third, hydraulic systems can improve the efficiency of CNC machine tool operation, and control the moving parts of machine tools and clutch, to provide basic support. Fourth, it can improve the lubricity of CNC machine tools, timely cooling, and help the worktable to complete daily actions [1].

1.2 Composition of hydraulic system of CNC machine tool

The hydraulic system of a CNC machine tool includes the main pump power station and corresponding control parts and accessories [2]. During the operation of the hydraulic system, the main actuator drives the workpiece or tool to directly participate in the movement of the workpiece surface, which has a very important impact on the stability and efficiency of the entire CNC machine tool operation.

1.3 Hydraulic compensation balancing device

For the gravity axis skateboard itself is extremely heavy (AB large swing Angle five coordinate CNC machine tool) and rectangular inlaid steel stick plastic guide rail structure, low speed and heavy load CNC machine tool, typically use hydraulic compensation balance. The hydraulic balance compensation system consists of a hydraulic station, a hydraulic balance cylinder, an accumulator component and a hydraulic balance compensation component. Hydraulic balancing device and separate hydraulic balancing and self-circulating hydraulic balancing two [3]. Currently, accumulators are widely used in self-circulating hydraulic compensation and balancing systems. It is divided into bladder accumulators, piston accumulators, and diaphragm accumulators, according to their construction and application. In open hydraulic balancing systems, variable hydraulic pumps, stroke CAM patterns and adjustable relief valve combinations are widely used. The difference between the two is the volume size of the accumulator and whether the hydraulic station runs regularly [4]. The balance structure of the hydraulic

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compensation balance system is complicated and the hydraulic values need to be checked and compensated regularly. The structure diagram is shown in Fig.1.

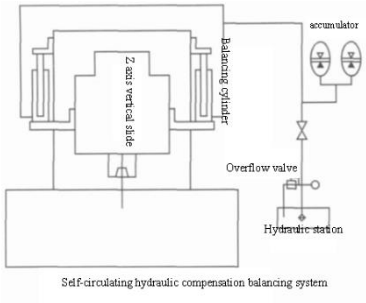

Figure 1 Hydraulic compensation balancing device

2. Hydraulic balance system design

2.1 Design scheme for a self-circulating hydraulic balancing system

Currently, researches on CNC machine tool hydraulic balance systems have not examined their overall balance properties, analysis of parameter correlation selection, and performance parameter impact relations in CNC machine tool applications, resulting in relatively large pressure fluctuations in the form of self-circulation. Therefore, this paper will provide a comprehensive analysis and design of self-circulating hydraulic balancing systems for CNC machine tools from the overall applicability point of view. First, determine the parameters of the hydraulic system. According to the current numerical control machine tool hydraulic system technology application status, the technical parameters mainly include the main parameters and general technical parameters. The main parameters mainly represent the specifications and working performance of CNC machine tools. The motion parameters mainly represent the motion speed of the fixture and tool rest.

Second, CNC machine tool main drive system design. According to the current numerical control machine tool hydraulic system operation status, the main drive speed specific includes of continuously variable transmission (CVT) and stepled-variable level. This paper focuses on CVT. In this design process, the designer mainly uses AC speed regulation motor, mainly using frequency conversion speed regulation way to adjust the speed. The higher the efficiency of speed regulation, the better the performance.

Third, the hydraulic system structure design. In the whole hydraulic system component, it is mainly to ensure that the cutting process and motion transmission can be carried out smoothly, and to ensure that the tool and tool run in accordance with the established motion trajectory. Hydraulic system components are essential execution parts of CNC machine tools, which can drive the workpiece or tool to participate in the surface formation movement, which has a very significant impact on the operation efficiency of CNC machine tools and product quality [5]. In order to ensure the stability of the overall structure of the hydraulic system, designers need to combine the specific design parameters and dynamic parameters to control the rotation accuracy of the machine tool, improve the strength, stiffness and shock resistance, and maintain excellent thermal stability and wear resistance.

2.2 Loop of self-circulating hydraulic balancing system

Figure 2 shows the circuit of the general self-circulation hydraulic balance system. The difference between Figure 2 (a) and Figure 2 (b) mainly lies in the way of filling oil. When working for a certain period of time, due to air leakage, oil leakage, there will be pressure drop. When the pressure drops to a certain extent, it is necessary to replenish the oil to ensure that it is close to the original oil pressure. Figure 2 (a) shows the manual oil filling circuit, the normal work is the cut-off valve, regularly or irregularly check the pressure gauge, when the pressure drops to a certain value (it can be agreed that the minimum balance force position is the inspection position), manually open the cut-off valve for oil filling. Figure 2 (b) shows the automatic oil replying circuit. The oil replying circuit adopts the reversing valve to close and open, and the normal work is in the cut-off state. The double-point pressure switch is used for monitoring. When the pressure drops to the lower limit value, a signal is sent out. The reversing valve is controlled by the control system to connect the oil supplement circuit, and it is closed when the oil supplement pressure reaches the upper limit value. The middle and low-grade CNC machine tools can use manual oil replenishment loop, and the middle and high-grade automatic oil replenishment loop. The oil replenishment circuit can be a branch of the total hydraulic system of the machine tool. Although the two typical circuits have different oil filling methods and different automatic control characteristics, the balance characteristics of the system are the same.

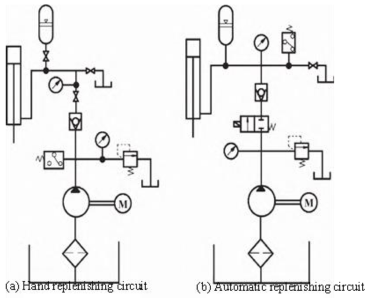

Figure 2 A typical circuit of a self-circulating hydraulic balancing system

2.3 Self-circulation hydraulic compensation balance system parameters

In the design state, that is, when the load W=0 on the rotary table, the oil chamber pressure is $p_{1,0}$ and $p_{2,0}$, respectively. In order to meet the needs of bearing capacity, the effective bearing area of the main and auxiliary oil pads should meet $Ae_1 > Ae_2$. Footer 1 and 2 denote the primary and secondary oil pads, respectively, and footer 0 denotes the initial state.

$$M_g=n_1p_{1,0}Ae_1-n_2p_{2,0}A_{e2} \quad (1)$$

Where ,M is Mass of rotating body (Kg).n_1/n_2 is The number of main and auxiliary oil chambers. $p_{1,0}$ /$p_{2,0}$ is initial pressure, Ae_1/ $Ae_2$is effective bearing area.

Then the mechanical balance equation of the rotating body in the adjustme nt process is as follows.

$$M_x''=W+ M_g -n_1p_{1,0}Ae_1+n_2p_{2,0}A_{e2} \quad (2)$$

Where, W is external load on the rotating body (N), $p_1/p_2$is Instantaneous pressure (MPa).

Under the working condition, considering the compressibility of hydraulic oil and the fluctuation of oil film caused by load change, the instantaneous flow continuity equation of oil pad at any time can be obtained as follows.

$$Q_i=\frac{P_i}{Rh,i}=Q_0-Q_{i,j}-Q_{i,r} \quad (3)$$

In the formula,Qi - the flow out of the oil pad due to the pressure of the oil chamber at a certain time (mL/min);Qj- Flow out of the oil pad due to the fluctuation of the oil film caused by the load (mL/min);Qrthe flow rate (mL/min) caused by the sensitive volume of the oil pad when the compressibility of the oil is considered;Q0 -- The flow rate (mL/min) provided by the quantitative oil supply system to the oil pad.

The fluctuation rate can better reflect the overall fluctuation degree of the balance force and the stationarity of the vertical components. Then,

$$\begin{cases} \lambda=\frac{\Delta F_P}{F_2} \\ F_1=\xi Sp_1=(1-\lambda)F_2=(1-\lambda)\xi Sp_2 \end{cases} \quad (4)$$

The definition and calculation of the volatility λ can also be based on the minimum balance force or the average balance force, with different numerical ranges but similar meanings. According to Equation (4).

The calculation is more appropriate, and the value of λ is $0 < \lambda \leq 1$. For λ= 1, it theoretically exists, that is, the minimum equilibrium force F1 is 0, but the real world is not chosen in this way. Due to the high requirements of CNC machine tools, the value of λ is very small, usually choose $\lambda \leq 0.1$, the higher the stationarity requirement, the smaller the value of λ.

In the design of vertical balance system of CNC machine tools, the volume change ΔV is usually known, and the maximum balance force F_2 and fluctuation rate λ are determined. The theoretical volume

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V_0 of the accumulator and the initial charging pressure p_0 are calculated, and the required initial oil filling pressure is actually p_2. Get:

$$V_0 = \frac{LS^{0.286}F_2^{0.714}p_0^{-0.714}}{\xi^{0.714}[(1-\lambda)^{-0.714}-1]} \tag{5}$$

According to equation (5), the theoretical volume V_0 of accumulator has a linear increasing relationship with movement stroke L, cylinder action area S and safety factor τ, and the balance force fluctuation rate

The λ is a nonlinear decreasing relationship, so the smaller the volatility requirement is, the larger the accumulator volume requirement is.

There are countless combinatorial solutions of (p_0, V_0), but in practical applications, certain values must be given, so one of these quantities should be determined first according to practical requirements. Examining the change process of the accumulator, when the balance is in the minimum balance force state, that is, in the (p_1, V_1) state, there must be a certain amount of oil in the accumulator, otherwise if there is overrange or leakage, the formation of negative pressure and failure, but also easy to lead to air bag damage. Therefore, the volume change is restricted,

$$\begin{gathered} p_0 = \frac{p_1}{\tau^{1.4}} = \frac{(1-\lambda)F_2}{\xi S\tau^{1.4}} \\ V_0 = \frac{LS_\tau}{1-(1-\lambda)^{0.714}} \\ p_2 = \frac{F_2}{\xi S} \end{gathered} \tag{6}$$

According to equation (6), the inflation pressure p_0 has a linearly increasing relationship with the balance force, an inverse relationship with the cylinder area S, a linearly decreasing relationship with the volatility λ, and a nonlinear decreasing relationship with the safety factor τ.

3. Hydraulic pressure adjustment requirements

In order to achieve the ideal balanced motion configuration of the vertical slide of the gravity axis, it is necessary to move the vertical slide of the gravity axis continuously within its stroke, and comprehensively adjust the motor load current and hydraulic pressure to ensure its synchronous and reasonable shift.

First ,the current values in the positive direction (I1 and I4) must be larger than those in the negative direction (I2 and I3). If the current value in the negative direction is greater than the current value in the positive direction, it may be that the hydraulic balance force is overly large, causing the motor to use a large load current to overcome the hydraulic buoyance and make the slide move down. If the hydraulic top force generated by the hydraulic balance pressure exceeds the motor load, it will cause the gravity axis vertical slide to move upward abnormal offset, cause the gravity axis vertical slide servo motor monitoring profile error is too large alarm and servo unit error alarm, and make the tool rise irregularly in the vertical direction, and the vertical dimension error of the workpiece increases after processing. That is, there is an effect of loss of motion.

Second, the current difference (I1-I2, I3-I4) between the forward and reverse axes at the upper and lower endpoints of the stroke should be as tiny as possible. If the current difference is large, it may be that the hydraulic balance pressure value is too narrow or the hydraulic balance element (accumulator, variable hydraulic pump or adjustable relief valve) adjustment or capacity selection error or damage, but also extremely easy to cause gravity axis vertical slide servo motor monitoring and servo unit frequent alarm. The hydraulic balance pressure value should be slowly increased, so that the forward and reverse direction axis movement current difference can be 0.3~1A. If the adjustment or capacity selection of the hydraulic balance element is wrong or damaged, the problem should be accurately found, and the faulty hydraulic element should be redesigned and replaced.

Third,the difference of hydraulic balance pressure (M2-M1) at the upper and lower endpoints of the stroke should be changed within a reasonable range. The hydraulic balance pressure value at the upper endpoint of the stroke is defined as M1, and the hydraulic balance pressure value at the lower endpoint is defined as M2. The reasonable variation range of the general pressure difference (M2-M1) is 0.8~4MPa. If the pressure difference is less than 0.3MPa, in the closed hydraulic balance system because the accumulator nitrogen pressure is insufficient or damaged, the accumulator loses the hydraulic balance force adjustment function; in the open hydraulic balancing system, the variable hydraulic pump variable

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structure is damaged or the stroke CAM pattern and adjustable relief valve combination mechanism fails. If the pressure difference is greater than 0.4MPa, the design capacity of the accumulator in the closed hydraulic balancing system is not sufficient to meet the requirements of the hydraulic balancing pressure storage volume. It is necessary to connect an accumulator with sufficient capacity on the basis of the original accumulator to solve this problem. In the open hydraulic balance system, the variable hydraulic pump variable mechanism is not set properly or the stroke CAM pattern and adjustable relief valve combination mechanism is not correct. 0.4MPa, in the closed hydraulic balance system is the accumulator design capacity is not sufficiently, can not meet the hydraulic balance pressure storage volume requirements, need in the original accumulator on the basis of a sufficient capacity of the accumulator can solve this problem. In the open hydraulic balance system, the variable hydraulic pump variable mechanism is not set properly or the stroke CAM pattern and adjustable relief valve combination mechanism is not correct.

Fourth,move the gravity axis skateboard to the top of the Z-coordinate working trip, and reliably support the gravity axis skateboard with wooden blocks. The vertical drive ball screw pair and the gravity axis vertical slide off, the dial indicator needle at the bottom of the gravity axis vertical slide, the table is set to zero, in order to observe the gravity axis vertical slide up the top of the tiny axial movement. Start the hydraulic system, and gradually increase the pressure of the hydraulic balance system by using the adjustable relief valve that controls the outlet pressure of the hydraulic power pump. The pressure of the hydraulic balance cylinder calculated before is 15.4MPa. Observe that the dial indicator hand does not change, indicating that the calculated value has an error. Slowly continue to increase the pressure of the hydraulic balance system to 16MPa, the dial indicator needle at the lower end of the vertical sliding plate of the gravity axis has 0.05mm upward movement, indicating that the actual hydraulic pressure in the hydraulic balance system is at least 16MPa, in order to provide upward balance force for the vertical sliding plate of the gravity axis. According to the above process, the gravity axis slide is moved to the top of the Z-coordinate working stroke, and the maximum pressure of the hydraulic balance cylinder is 20MPa.

4. Simulation analysis

A 5-coordinate AC swing Angle gantry CNC milling machine, gravity axis slide for the Z coordinate. It is known that the vertical slide plate and auxiliary parts weigh 2t, the spindle parts weigh 0.2t, the gearbox and the spindle motor weigh 0.5t, and the swing Angle transmission mechanism weighs 0.5t. The vertical skateboard movement distance of the gravity axis is 800mm. The fast feed speed is 10m/min. The energy-saving and reliable closed hydraulic balance system is adopted. Two single-acting plunger hydraulic cylinders are installed on both sides of the gravity axis slide plate to provide hydraulic compensation and balance force. The piston rod diameter is 36mm, and the working stroke is 1000mm. The structure can be referred to Figure 3.

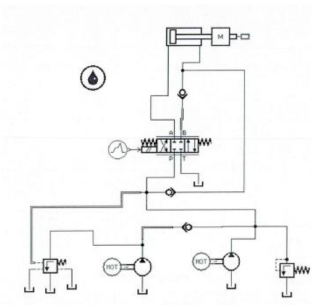

Figure 3 Loop model

According to the displacement of the selected large and small pumps after calculation, the hydraulic pump parameters were set to 16,6.3 cc/rev, respectively. The motor speed parameter is set to 1450r/min. The pressure value of the relief valve is set to 40bar. The pressure value of the unloading relief valve was set to 35bar. The parameters of the hydraulic rainbow are set as 80mm cylinder diameter, 55mm hydraulic rod diameter, 2m stroke, 4000kg friction resistance of the mass of the pushing object, and 2000N friction resistance.

From the simulation results, when the signal value is -3.5, 3.5, the corresponding hydraulic rod working speed is 0.017m/s, namely 1m/s.When the signal value is -28 and 32, the corresponding quick forward and backward speed of the hydraulic rod is 0.13m/s, or 8m/s. The data are consistent with the

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design requirements. Due to the ramp function of the amplifier controlling the proportional directional valve, the speed conversion process is smooth and excessive without impact. However, according to the overflow flow of unloading valve, the oil spillover from unloading is about 13L/min in rapid forward and rapid backward, which seems slightly large because the simulation does not consider the leakage of pump. Therefore, there are some errors in the test results.

5. Conclusion

In this paper, the self-circulation hydraulic balance system is designed based on the characteristics of CNC machine tools, and the balance force fluctuation and fluctuation rate are incorporated into the hydraulic balance system parameter system, and the complete parameter calculation relationship of the self-circulation hydraulic balance system is given, which further enriches the mechanism principle design of the main mechanical structure of the machine tool, and provides theoretical support for the development of CNC machine tools .

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