Analysis on dynamic precision degradation mechanism of high-speed precision press

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Abstract: With the increase of service time, the dynamic precision of high-speed precision press is getting lower and lower. In order to study the precision degradation mechanism, a dynamic model of main transmission system of high-speed precision press was established based on ADAMS, and the influence of different bearing clearance on the dynamic precision was studied. The simulation results show that the dynamic precision of bottom dead center (BDC) decreases with the increase of joint clearance. And the increase of the joint clearance between main linkage and main slider has the greatest impact on the dynamic accuracy of BDC, the impact of the joint clearance between crankshaft and major linkage is smaller, and the impact of the joint clearance between crank shaft and bearing is the smallest. Finally, the field test was carried out. The analysis of the test data shows that the wear of the bearings in the main drive system leads to the increase of the clearance, which leads to the degradation of the dynamic precision.

1. Introduction

As an efficient forging and pressing equipment, the high-speed punch machine is widely applied in many important industrial fields, such as aerospace, automobile manufacturing, transportation, metallurgy and chemical industry[1]. With the acceleration in the space of the market globalization, the competition is becoming more intense, and higher requirement for the dynamic precision of the forging equipment has been put forward. The precision of high-speed punch has always been a hot issue, which has been widely concerned by scholars[2-3]. Based on ADAMS, Hu et al.[4] built the dynamic modeling of multi-rod mechanical press to investigate how the joints clearance for multi-rod mechanical press influence the repeat accuracy of BDC. Hu et al. [5] built a dynamic model for the multi-rod high-speed press and analyzed the influence of elastic deformation and elastic waves on dynamic accuracy of the BDC. Xiao et al.[6] analyzed the influence of machining error, elastic deformation and joint clearance on the reliable precision reliability of high-speed precision press. Considering the actual features such as clearance, flexibility and friction, Chen et al.[7] developed a rigid-flexible model to analysis the dynamic precision of a high-speed heavy load press. Thus it can be seen that the dynamic precision of the BDC is mostly determined by machining error, elastic deformation and joint clearance[8].

The second part of this paper uses the J76-80 press as an example to establish a dynamic model with joint clearances based on ADAMS. The third section analyzes the influence of each joint clearance for dynamic precision of BDC. A field test was carried out to determine dynamic precision degradation mechanism in the fourth section. Finally, a concluding summary was presented by comparing simulation results with test results.
2. Dynamic model of transmission system

2.1. Driving mechanism of high-speed press with joints clearance

The diagram of driving mechanism of J76-80 press with joint clearance is shown in Figure 1. The joint clearance between crank shaft and bearing seat is $e_1$. The joint clearance between crankshaft and major linkage is $e_2$. The joint clearance between main linkage and main slider is $e_3$.

![Figure 1. J76-80 press driving mechanism with joint clearance.](image1)

2.2. Kinematic pair model with clearance

2.2.1. Rotating joint model with clearances

Rotating joint model with clearances is shown in Figure 2. Assume that the radius of shaft is $r$, the radius of bearing is $R$. The clearance of rotating joint is

$$e = R - r$$  \hspace{1cm} (1)

Assume that the center of bearing is $O_1$, the center of shaft is $O_2$. The distance between $O_1$ and $O_2$ is

$$l_1 = \sqrt{x_{O2}^2 + y_{O2}^2}$$  \hspace{1cm} (2)

where $x_{O2}$ and $y_{O2}$ are the coordinates of $O_2$.

Normal penetration depth of shaft and bearing is

$$\delta_1 = l_1 - e = \sqrt{x_{O2}^2 + y_{O2}^2} - (R - r)$$  \hspace{1cm} (3)

where $\delta_1 \geq 0$ indicates that the bearing collides with the shaft, $\delta_1 < 0$ indicates that the bearing is separated from the shaft.

![Figure 2. Rotating joint clearance](image2)

2.2.2. Spherical joint model with clearance

Spherical joint model with clearances is shown in Figure 3. Assume that the radius of ball head is $sr$, the radius of ball bearing is $SR$. The clearance of spherical joint is

$$E = SR - sr$$  \hspace{1cm} (4)
Assume that the center of ball bearing is SO1, the center of ball head is SO2. The distance between SO1 and SO2 is

$$l_2 = \sqrt{x_{SO2}^2 + y_{SO2}^2 + z_{SO2}^2}$$  \hspace{1cm} (5)

where $x_{SO2}, y_{SO2}$ and $z_{SO2}$ are the coordinates of SO2.

Normal penetration depth of ball head and ball bearing is:

$$\delta_2 = l_2 - E = \sqrt{x_{SO2}^2 + y_{SO2}^2 + z_{SO2}^2} - (SR - sr)$$  \hspace{1cm} (6)

where $\delta_2 \geq 0$ indicates that the ball bearing collides with the ball head, $\delta_2 < 0$ indicates that the ball bearing is separated from the ball head.

![Figure 3. Spherical joint model with clearance](image)

2.3. Contact force model

According to the nonlinear continuous impact contact force model, the contact force $F$ is

$$F = \begin{cases} 0 & \text{if} \quad \delta < 0 \\ F_N + F_T & \text{if} \quad \delta \geq 0 \end{cases}$$  \hspace{1cm} (7)

where $F_N$ is normal contact force, $F_T$ is tangential contact force, $\delta$ is normal penetration depth.

Normal contact force $F_N$ can be calculated according to Eq. (8).

$$\begin{cases} F_N = K\delta'' + C(\delta)\delta & \delta > 0 \\ 0 & \delta \leq 0 \end{cases}$$  \hspace{1cm} (8)

where $C(\delta)$ is transient damping coefficient, $K$ is the contact stiffness coefficient. It can be calculated according to Eq. (9).

$$K = \frac{4}{3\pi(h_i + h_j)} \left( \frac{D_iD_j}{D_i + D_j} \right)^{\frac{1}{2}}$$

$$h_k = \frac{1 - \nu_k^2}{\pi E_k} \quad k = i, j$$

$$D = \frac{D_iD_j}{D_i + D_j}$$  \hspace{1cm} (9)

where $D_i$ is the radius of the bearing, $D_j$ is the radius of the bearing and shaft, $h_k$ is the material properties of bearing and shaft, $\nu_k$ is the poisson’s ratio of bearing and shaft, $E_k$ is the elastic modulus of bearing and shaft.

Transient damping coefficient $C(\delta)$ can be calculated according to Eq. (10).

$$C(\delta) = \begin{cases} 0 & \delta \leq 0 \\ C_{max} \left( \frac{\delta}{\delta_{max}} \right)^2 \left( 3 - 2 \frac{\delta}{\delta_{max}} \right) & 0 < \delta < \delta_{max} \\ C_{max} & \delta \geq \delta_{max} \end{cases}$$  \hspace{1cm} (10)

where $\delta_{max}$ is maximum contact depth, $C_{max}$ is maximum damping coefficient.

In this paper, the modified Coulomb friction model is used to describe the tangential contact force $F_T$. It can more truly reflect the actual movement and improve the accuracy of simulation[4].
2.4. Dynamic model of transmission system

According to Figure 1, we know that the transmission system is a crank slider mechanism, as shown in Figure 4. Combining Figure 1 and Figure 5, the simulation model of transmission system is built based on ADAMS. The parameters are as follows: the radii of crank $l_1$ and $l_1'$ are 15mm and 25mm respectively, the mass of crank $m_1$ is 437kg, the length of main linkage $l_1$ is 350mm, the mass of crank $m_2$ is 206kg, the mass of main slider $m_3$ is 1470kg, the length of auxiliary linkage $l_2'$ is 520mm, the mass of auxiliary linkage $m_2'$ is 77kg, the mass of auxiliary slider $m_3'$ is 1287kg.

3. Analysis of the influence of clearances on dynamic precision

3.1. Influence of joint clearance $e_1$ on dynamic precision

In order to study the influence of joint clearance $e_1$ on dynamic precision, the joints clearance $e_2$ and $e_3$ are set to 0. By measuring, we determine that the joint clearance $e_1$ of the new press is about 0.04mm and it is about 0.12mm after three years. Therefore, joint clearance $e_1$ is set as 0.04mm, 0.06mm, 0.08mm, 0.10mm, 0.12mm and 0.14mm respectively in simulation model. The simulation results are shown in Figure 6. Figure 6 shows, with the increase of joint clearance $e_1$, the mean value of dynamic precision of BDC increases gradually. When $e_1$ increases from 0.04mm to 0.14mm, the average dynamic accuracy of BDC increases from 0.45μm to 0.86μm, and the increment is 0.41μm.

3.2. Influence of joint clearance $e_2$ on dynamic precision

Similarly, the joint clearance $e_1$ and $e_3$ are set to 0. By measuring, we determine that the joint clearance $e_2$ of the new machine tool is about 0.07mm and it is about 0.11mm after three years. Therefore, joint clearance $e_2$ is set as 0.06mm, 0.07mm, 0.08mm, 0.09mm, 0.10mm and 0.11mm respectively in simulation model. The simulation results are shown in Figure 7. Figure 7 shows, with the increase of $e_2$, the mean value of dynamic precision increases gradually. When $e_2$ increases from 0.06mm to 0.14mm, the average dynamic accuracy of BDC increases from 0.45μm to 0.86μm, and the increment is 0.41μm.
0.11mm, the average value of dynamic precision increases from 2.96μm to 6.54μm, and the increment is 3.58μm. Compared with $e_1$, the increase of $e_2$ has a greater impact on the dynamic precision.

3.3. Influence of joint clearance $e_3$ on dynamic precision

Similarly, joint clearance $e_3$ is set as 0.050mm, 0.055mm, 0.060mm, 0.065mm, 0.070mm and 0.075mm respectively in simulation model. The simulation results are shown in Figure 8. Figure 8 shows, with the increase of joint clearance $e_3$, the mean value of dynamic precision of BDC increases gradually. When $e_3$ increases from 0.050mm to 0.075mm, the average value of dynamic precision increases from 8.10μm to 25.10μm, and the increment is 17μm. Compared with $e_1$ and $e_2$, the increase of $e_3$ has the greatest impact on the dynamic precision.

Figure 8. Average value of dynamic precision at different joint clearance $e_3$

4. Experimental study

In reality, it is impossible to set joint clearance to 0. It is impossible to carry out the experiment according to the simulation. So we select the high-speed press with different service time to measure the total joint clearance $e$ ($e=e_1+e_2+e_3$) and dynamic precision. The press and the measuring system for the test is shown in Figure 9.

The test results are shown in the Figure 10 and 11. Figure 10 shows, with the increase of service time, dynamic precision of BDC is declining and the deceleration increases continuously. And, it can be found from Figure 11 that total joint clearance has the same change rule.
By synthesizing Figure 10 and Figure 11, the curve of dynamic precision at different total joint clearances is obtained, as shown in Figure 12. Figure 12 shows, with the increase of the total clearance, dynamic precision of BDC is declining. To sum up, the joint clearances of bearings become larger due to wear during service, which leads to the degradation of the dynamic precision of BDC.

5. Conclusions
By establishing the dynamic model of transmission system, the influence of different joint clearances to dynamic precision is analyzed. And on this basis, the experimental research is carried out. The conclusions are as follows:

1) With the increase of the joint clearances, dynamic precision of BDC decreases continuously. The increase of $e_3$ (the clearance of the ball bearing) has the greatest impact on the dynamic accuracy, $e_2$ (the joint clearance between crankshaft and major linkage) takes the second place, and $e_1$ (the joint clearance between crank shaft and bearing seat) has the least impact.

2) The degradation mechanism is that with the increase of service time the clearances of the bearings is also increasing, which leads to the degradation of BDC.

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