Dynamic analysis of main transmission mechanism of high-speed cold heading machine based on rigid-flexible coupling model

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Abstract: In the research of high speed cold heading machine, only single part is studied. The interaction between the components of the main drive mechanism is rarely studied. The motion of the main transmission mechanism of the cold heading machine was analysed. The interaction between the components of the main transmission mechanism was studied. This article adopts the theory of multi-body system dynamics. The rigid-flexible coupling model of the main transmission mechanism was established. The dynamics and kinematics simulation of the main transmission mechanism was carried out. The motion curve and stress of the rigid-flexible coupling model are obtained. Compared with the rigid model, the rationality of the rigid flexible coupling model was demonstrated. It provided a reference for further fatigue analysis and optimization of the main transmission mechanism.

1. Introduction
Cold heading machine, a machine that uses cold heading technology to make metal plastically deform at room temperature, is mainly used for the processing and production of fasteners such as screws and nuts [1]. With the continuous development of manufacturing industry and the large demand for high-precision and high-quality fasteners, high-quality, high-speed and high degree of automation have become the development trend of cold heading machine [2]. As the key component of cold heading machine, the working condition of main transmission mechanism often directly affects the overall performance index of cold heading machine, and also affects the quality and performance of cold heading products. However, in the research of high-speed cold heading machine, most of them only focused on single part. The interaction between the components of the main drive mechanism is often not considered. The research on the main transmission mechanism of high speed cold heading machine is still insufficient [3]. And the modeling methods are basically rigid model, and there are some deviations from the actual situation.

In view of the above problems, the rigid model and rigid-flexible coupling model were established respectively by using the multi-body system dynamics theory. The dynamics of the main transmission mechanism of cold heading machine under different models was studied. Through comparative analysis, it provides reference for other research and analysis of cold heading machine.
2. Theory of multibody system dynamics

According to the mechanical characteristics of the objects in the system, the multi-body system can be divided into multi-rigid body system, flexible multi-body system and rigid-flexible coupling multi-body system. Multi rigid body system refers to that the elastic deformation of the object in the system can be ignored and treated as a rigid body. Flexible multi-body system refers to the coupling of the large-scale movement of the object and the elastic deformation of the object during the movement of the system. The rigid-flexible coupling multi-body system is between the multi-rigid body system and the flexible multi-body system. It refers to the existence of part of the flexible body in the rigid body system [4].

The general form of the multi-body system dynamics model [5] can be expressed as:

\[
\begin{aligned}
\dot{\Phi} + \Phi_T \lambda &= B \\
\Phi(\theta, t) &= 0
\end{aligned}
\] (1)

The rigid-flexible coupling model is based on the rigid model. The flexible body in rigid flexible coupling model can be discretized by modal analysis method. The modal analysis method uses modal coordinates to describe the changes of components over time. According to modal synthesis and modal truncation, the purpose of reducing the solution scale is achieved. A flexible body can be regarded as a collection of nodes of a finite element model, and its deformation is a linear superposition of modal modes [6]. The modal coordinates of a flexible body [7] can be expressed by the following formula.

The position of the node \( p \) on the flexible body is the sum of 3 vectors:

\[
\gamma_p = x + s_p + u_p
\] (2)

Where \( x \) is the position vector from the origin of the local coordinate system to the origin of the local coordinate system; \( s_p \) is the undeformed position vector of node \( p \) in the local coordinate system; \( u_p \) is the linear deformation vector of point \( p \).

Let \( \psi = [\psi, \theta, \phi]^T \), \( \psi, \theta \) and \( \phi \) are Euler angles in \( x, y, z \) directions of the local coordinate system relative to the origin of the global coordinate system; \( X = [x, y, z]^T \), \( x, y, z \) are the positions of the local coordinate system relative to the global coordinate system; \( q[q_1, \ldots, q_n]^T \), \( q_m \) is the mode component of the mode \( m \) amplitude. The generalized coordinates of the flexible body can be expressed as:

\[
\zeta = [X^T, \psi^T, q^T]^T
\] (3)

3. Establishment of rigid-flexible coupling model

This paper takes the main drive mechanism of JYX15-30GA high-speed screw cold heading machine as the research object. The machine mainly produces screws from M3 to M7. The cold heading machine completes one screw, and the motor turns two turns to complete the forming of screw head and zigzag or cross flower respectively. The output of cold heading machine is 300 grains per minute, so the motor speed is 600 r/min. The movement period of the main transmission mechanism is 0.2s.

3.1. Stress analysis of crankshaft

The main transmission mechanism of cold heading machine includes flywheel, crankshaft, connecting rod and slider. The force of the main transmission mechanism is more complicated, mainly affected by the cold heading force, the driving force of the motor and the friction force. Obviously, it is not easy to analyse the force of the whole main drive mechanism. As an important component of the main transmission mechanism, the crankshaft has a direct impact on the normal operation of the entire main transmission mechanism and the entire cold heading machine. Therefore, it is meaningful to analyse the force on the crankshaft.

The stress of crankshaft is analysed, and the stress condition of crankshaft is shown in Figure 1. \( F_1 \) and \( F_2 \) are the two cold heading forces received by the crankshaft, which are obtained by formula (3). Min is the input torque and \( M_{out} \) is the output torque. According to the torque transmission formula of the motor, \( M_{in} = 47.25 \text{Nm} \).
Figure 1. Stress analysis of crankshaft.

Cold heading force can be calculated by formula:

\[ P = Z \times N \times \delta_1 \left( 1 + d \mu \frac{D}{4H} \right) F \]  

(4)

- \( P \) — cold heading force, N;
- \( Z \) — deformation factor;
- \( F \) — projected area of head tool contact, mm²;
- \( D \) — cold head diameter, mm;
- \( N \) — tool shape factor;
- \( H \) — head height of cold heading, mm;
- \( \delta_1 \) — tensile strength of cold heading material, MPa;
- \( \mu \) — frictional coefficient.

The calculated cold heading force \( F_1 \) is 65851N and \( F_2 \) is 34276N. The cold heading forces \( F_1 \) and \( F_2 \) directly act on the movable mold of the sliding table. The cold heading force acts on the shaft diameter of the C end of the crankshaft through the sliding table and the connecting rod.

3.2. Establishment of rigid flexible coupling model

According to the force analysis of the main transmission mechanism, the crankshaft is established as a flexible body in the rigid flexible coupling model. The 3D model of the main transmission mechanism is established by SOLIDWORKS software. Import the model into ADAMS software. The rigid model can be obtained by adding constraints between the corresponding components.

On the basis of the rigid model, a flexible crankshaft (a modal neutral file with the suffix .MNF) is used to replace the rigid crankshaft in the rigid model. The rigid-flexible coupling model of the main transmission mechanism can be obtained, as shown in Figure 2. Through the establishment of the rigid-flexible coupling model of the main transmission mechanism, it is compared with the rigid model. It is helpful to analyze the structural characteristics and movement characteristics of the main transmission mechanism more effectively.

Figure 2. The rigid-flexible coupling model of the main transmission mechanism.

4. Dynamic analysis of main transmission mechanism

The cold heading machine produces 300 screws per minute with a speed of 600r/min. The cycle required to complete a screw is 0.2s. Add constraints and driving forces to the model. Set the simulation time to 0.2 and the step size to 0.002. The rigid model and rigid-flexible coupling model were respectively simulated for motion. Through post-processing, the simulation results and data can be viewed.
4.1. Analysis and Comparison of Rigid Model and Rigid-flexible Coupling Model

Figure 3 shows the displacement, velocity and acceleration curves of the sliding table. Picture (a) is a rigid model, (b) is a rigid-flexible coupling model. It can be seen from the figure that the displacement of the sliding table is 40mm, the speed is about 1200mm/s, and the acceleration is about 7500mm/s². Under the action of periodic load, the displacement, velocity and acceleration curves of the sliding table all show periodic changes. In the picture (a), the displacement, velocity and acceleration curves of the sliding table are smooth, without any fluctuations or sudden changes. That is, the movement of the sliding table has not changed under the action of the cold heading force, and is still stable. In picture (b), it can be seen that the acceleration of the sliding table changes suddenly and fluctuates under the action of cold heading force within 0.025-0.030s and 0.125-0.130s.

Comparing the speed and acceleration curves of crankshaft and connecting rod under different models, as shown in Figure 4 and Figure 5. The speed and acceleration curves of crankshaft and connecting rod also have periodicity. The speed of the two different models has not changed. However, the acceleration curve is similar to that of the slide. Both of them have mutation and fluctuation under the action of cold heading force. Take the crankshaft as an example, the acceleration of the crankshaft under the rigid model is 12500mm/s². The acceleration under the rigid-flexible coupling model has a sudden change. The acceleration of the crankshaft suddenly changes to 29000mm/s² when subjected to cold heading force \( F_1 \). Similarly, the acceleration of the crankshaft produces fluctuations in the cold heading force \( F_2 \). The motion curve of connecting rod is similar to that of crankshaft.
Figure 4. Speed and acceleration curve of crankshaft.

(a). Rigid model

(b). Rigid-flexible coupling model

Figure 5. Speed and acceleration curve of connecting rod.

(a). Rigid model

(b). Rigid-flexible coupling model
Joint 6 is the rotation pair constraint between the crankshaft and the connecting rod. The force and torque curve of constraint 6 is shown in Figure 6. Comparing the curves under different models, it can be found that the force between the crankshaft and the connecting rod has not changed due to the flexibility of the crankshaft. The magnitude of the cold heading force between the crankshaft and the connecting rod is approximately 66000N and 35000N. It is basically consistent with the result calculated by formula (4). Although the torque varies in the rigid model, its value is small, only 5E-3Nmm. Compared with the torque 5E+4Nmm under the rigid-flexible coupling model, the torque under the rigid-flexible coupling model can be ignored.

The kinematic characteristic curve, force and torque curve of the main drive mechanism under different models are compared and analyzed. It can be seen that the motion of the main transmission mechanism in the two models changes periodically under periodic load. However, the elastic deformation of the object is ignored in the rigid model. Therefore, the deformation of acceleration curve is ignored in the rigid model. In the rigid flexible coupling model, the deformation is shown. The rationality of the rigid-flexible coupling model is verified.

4.2. Stress Analysis of Rigid-flexible Coupling Model
Through the rigid-flexible coupling simulation of the main drive mechanism, the stress and strain of the flexible crankshaft at different times can be obtained. Because there is no flexible body in the rigid model, the stress and strain of the component can not be obtained.

The 10 nodes with the highest stress on the flexible crankshaft are shown in Table 1. The maximum stress of the crankshaft occurs at about 0.026s, when the cold heading force begins to become zero. The maximum stress is 19.47MPa. The maximum stress node number is 288. The occurrence position X=379.5mm is where the shaft diameter of section C of the crankshaft connects with the left end shoulder. Moreover, the positions of the 10 nodes with the largest stress are concentrated in the C section...
shaft diameter and the left shoulder of the crankshaft. Therefore, special attention should be paid to the stress concentration at the fillet.

Table 1. The 10 Maximum stress nodes of the crankshaft.

| Spot # | Stress (n/mm²) | Node id | Time (sec) | Location (mm) |
|--------|----------------|---------|------------|---------------|
| 1      | 19.47          | 288     | 0.026      | 379.5, -69.9, 2.2 |
| 2      | 16.97          | 287     | 0.026      | 379.5, -69.9, 3.7 |
| 3      | 16.47          | 284     | 0.026      | 379.5, -69.5, 8.1 |
| 4      | 16.41          | 494     | 0.026      | 481.5, -69.5, 8.1 |
| 5      | 16.04          | 4194    | 0.026      | 378.5, -69.8, 2.5 |
| 6      | 15.95          | 285     | 0.026      | 379.5, -69.6, 6.6 |
| 7      | 15.56          | 493     | 0.026      | 481.5, -69.3, 9.5 |
| 8      | 15.54          | 2298    | 0.026      | 482.9, -69.4, 8.8 |
| 9      | 15.37          | 2297    | 0.026      | 482.9, -69.6, 7.3 |
| 10     | 15.02          | 2299    | 0.026      | 482.9, -69.2, 10.2 |

5. Conclusion

In the research of high-speed cold heading machine, there is a lack of overall research on the main transmission mechanism Considering the interaction between the components of the main drive mechanism. In this paper, the crankshaft was established as a flexible body by using the rigid-flexible coupling model method. The dynamics simulation of the main transmission mechanism was carried out. Through post-processing, the kinematic characteristics and stress of the main transmission mechanism under the rigid-flexible coupling model were obtained. Compared with the rigid model, the rationality of the rigid flexible coupling model was demonstrated. Through the above simulation analysis, it provides ideas and references for subsequent fatigue analysis and research on the main drive mechanism of the high-speed cold heading machine.

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