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Clearance Fit Design of a Hydraulic Cylinder with Particle Polluted by Hydraulic Oil

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Abstract: *In hydraulic cylinder systems, oil pollution results in wear and leakage of hydraulic cylinder components. In accordance with the actual working conditions of a certain type of hydraulic cylinder, the technology of fluid–solid thermal coupling and multiphase flow analysis is applied to analyze the heat–fluid–solid coupling of hydraulic cylinder under the condition of particle polluted by hydraulic oil. The distribution law of the heat field of hydraulic cylinder was obtained through analysis. The results show the effect of heat flow on the partial load effect. The distribution rules of particles in the hydraulic cylinder were obtained under the influence of different gaps and particle pollutants. The damage rate of the hydraulic cylinder under these working conditions was analyzed by optimizing the plunger and cylinder clearance fit and providing important technical support to solve the problem of hydraulic oil leakage in hydraulic cylinders.*

Keywords: *clearance fit, damage rate, hydraulic cylinder, leakage, thermal fluid–solid coupling*

1. Introduction

Hydraulic equipment is widely used in petrochemical and engineering machinery because of a variety of advantages. Leakage in hydraulic cylinders has a direct impact on service life and processing accuracy [1]. The maintenance mode of hydraulic cylinders in many enterprises still remains simple replacement, the service cycle of hydraulic cylinders is short, and the failure rate and maintenance cost are high after simple maintenance [2]. However, we need to analyze the cause of hydraulic cylinder leakage to ensure the normal operation of hydraulic cylinder equipment.

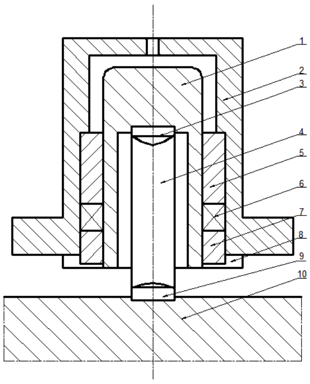
According to statistics, 70%–80% of malfunctions in hydraulic systems are caused by hydraulic oil pollution [3]. Once the oil of the hydraulic system is polluted by particles [4], it aggravates the wear of the original parts in the hydraulic cylinder, reduces sealing performance, and produces leakage. When pollutants enter the hydraulic cylinder, there is generally a gap of 0.5 mm between the outer circle of the piston and the cylinder [5]. In particular, a biased load affects the hydraulic cylinder, resulting in cylinder pulling and damaging the equipment [6]. Therefore, it is particularly important to study the particle pollution of hydraulic cylinders under a partial load. In prior work, the clearance fit of hydraulic cylinders was designed to improve the service life of the hydraulic cylinders.

There are many studies on the fluid-structure coupling analysis of hydraulic cylinders [7]. Research is seldom performed on hydraulic cylinder clearance fit in light of particle pollution and heat–fluid–structure interaction. Therefore, it is important to research the fluid–structure–thermal coupling of hydraulic cylinders with particle pollution under actual working conditions [8]. In this paper, we optimize the gap between the plunger and the cylinder with a method using DMP (Discrete Phase Model) thermal–fluid–solid coupling analysis technology so that the influence of hydraulic oil particle pollution on the leakage of the hydraulic cylinder is reduced to minimum. The results of the optimized hydraulic cylinder clearance were obtained through analysis.

2. Basic Principle and Model Structure

2.1. Basic principle

As the executive element of a compression machine, the hydraulic mechanism mainly completes the linear reciprocating movement [9] and converts high-pressure liquid pressure to mechanical power. When the compression machine works under a partial load, the polluted particles accelerate the influence of wear between the hydraulic cylinder and piston. The temperature of the guide sleeve will rise with the influence of wear, causing the expansion deformation of the guide sleeve [10,11]. This deformation of the hydraulic cylinder will produce displacement effects, so the temperature change is very important in the process of analysis, the combination of the partial load effect, fluid, and thermal analysis, such as a two-phase flow of particle study is necessary to bring the results closer to the actual situation. A schematic diagram of the hydraulic cylinders working principle is shown in Figure 1.



(1) Plunger, (2) cylinders, (3) hinge on the ball, (4) connecting rod, (5) guide sleeve, (6) seal, (7) pressing sleeve, (8) plunger gland, (9) under the spherical hinge, (10) walking beam.

Figure 1: Structure of the cylinder.

2.2. Model structure

The hydraulic cylinder of a fast-forging press is used as the research object in this paper. Solidworks software was used to build and assemble the 3D hydraulic cylinder model. Figure 2 shows the established 3D model. The main structure includes a cylinder block, plunger, guide sleeve, sealing device, and compression device. A cylinder block is generally made of cast steel with high stiffness and toughness, while a plunger is generally made of 45 steel, which plays a one-way sliding role along the guide sleeve. Especially under the influence of eccentric action, plunger deflection and guide sleeve contact damage will occur [12,13]; guide sleeve has high relative hardness. The guide sleeve plays a guiding role in reciprocating movement and is generally processed with bonze. The seals are mainly used to prevent leakage out of the hydraulic systems, as the failure of the sealing device will directly cause instability of the working movement.

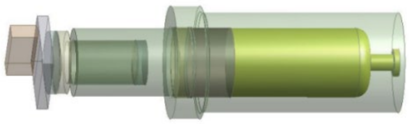


Figure 2: Structure of the cylinder

The above hydraulic cylinder model was imported into Workbench to form fluid model, as shown in Figure 3.

Figure 3: Fluid model

This section will be divided into subheadings. It is meant to provide a concise and precise description of the experimental results and their interpretation, as well as the experimental conclusions that can be drawn.

3. Analysis with Workbench

3.1. Mesh generation

In the process of meshing, due to the large differences in the dimensions of fluid domains, different meshing methods for different sub-regions are adopted to obtain high-quality fluid meshes. The tetrahedron meshing method is used for regular geometric models, while the tetrahedral meshing method is used for irregular geometric models [14]. Due to a clearance of the oil film thickness of only 0.5 mm, to ensure the mesh quality of the boundary layer, the height of the first layer of the grid and boundary were controlled during the meshing, as shown in Figure 4.

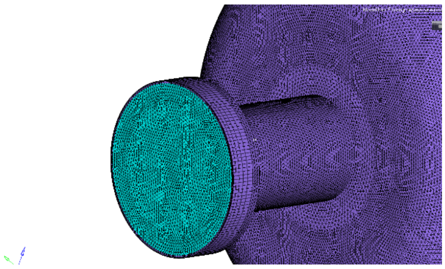


Figure 4: Model of the fluid meshing

To improve the calculation accuracy, meshing refinement was carried out. An enlargement of the local grid is shown in Figure 5 below.

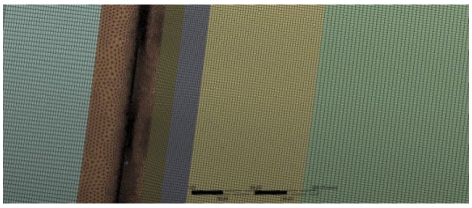


Figure 5: Locally amplified meshing

Figure 6 shows the whole structural meshing division. The workpiece and other parts have regular shapes, so the hexahedral meshing method was used to control the size of the surface meshing to obtain a better-quality grid. The tetrahedral meshing method is used for irregular models, which have irregular shapes. The overall grid quality is high.

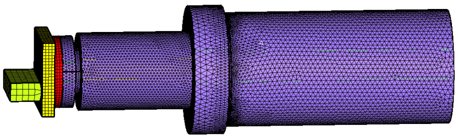


Figure 6: The whole model meshing

In CAE analysis, there is an inevitable error between numerical simulation and experimental values, and the approximation of physical models will also lead to deviations in calculation results. The resulting deviation error decreases with the thinning of the grid, and the number of grids increases. The number of discrete points increases, and the rounding error also increases. However, as the number of grids increases, the calculation cost increases, so the result within a certain range is closer to the actual value; thus, grid independence verification is carried out according to the number of grids [15]. The grid numbers 30,000, 60,000, 90,000, 120,000, and 150,000 were used for checking the results quality. Figure 7 shows the curve relationship between the grid number and the stress of the guide sleeve. With an increase in grid density, when the grid number is about 100,000, the stress of the guide sleeve tends to be stable, so the grid number is used for calculation.

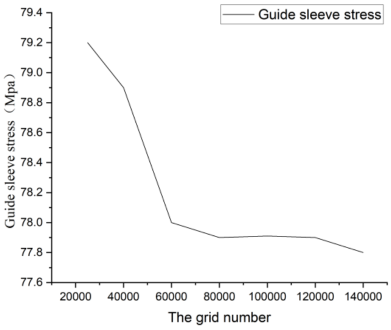


Figure 7: The calculation accuracy changes with the number of grids

4. Calculation and analysis

4.1. Boundary conditions and solver setting

Boundary condition setting and fluid simulation are driven by boundary conditions, and the solution process is to extend the data on the boundary surface to the internal computing domain [16]. Therefore, the selection of boundary conditions is directly related to the accuracy of the internal flow field simulation. In the simulation, the hydraulic oil density was 980 kg/m^3, the dynamic viscosity was 0.039 kg/m*s, the clearance end was set as the velocity inlet, the plunger movement velocity was set as 0.35 m/s, and the oil inlet was set as the pressure outlet. This combination is quite consistent with the actual situation in all aspects, and the Reynolds number of the flow field calculated was about 105 orders of magnitude. The fluid was in a turbulent state, and the turbulence model was selected for analysis and calculation in the following fluid models.

Hydraulic cylinder structure analysis belongs to typical assembly body contact analysis, where an appropriate contact relationship between different parts is especially important according to the working principle of the hydraulic cylinder. The contact between the ball hinge, middle rod, guide sleeve, and plunger is set as the standard contact, while the friction factor is 0.4. Other contacts are set as binding contacts to constrain the movement of the cylinder block, and 31 MPa pressure is applied to the workpiece.

4.2. Thermal analysis

Temperature affects the plunger displacement of a hydraulic cylinder, and the temperature of the guide sleeve varies between 30 ℃ and 60 ℃. Therefore, the temperature field distribution of the hydraulic cylinder at 30 ℃, 40 ℃, 50 ℃, and 60 ℃ was analyzed. It can be seen in Figure 8 that with an increase in temperature, the influence of temperature on the hydraulic cylinder clearly increases, and the maximum temperature is mainly concentrated in the guide sleeve part.

Figure 8 shows the temperature distribution of the guide sleeve. It can be seen in the figure that the deformation at both ends of the copper sleeve is the largest, and the maximum deformation is 0.2 mm. In practical work, this deformation will aggravate the pollution particles and the wear of the hydraulic cylinder.

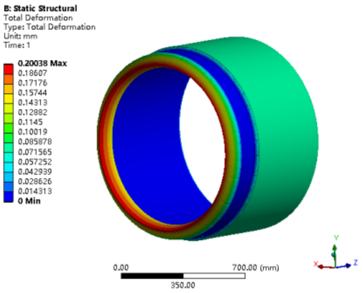


Figure 8: Thermal deformation of the guide sleeve

The calculation formula of radial force when the workpiece is deflected is given in the literature [17] :

$$F = 2rF_G / l = 2\pi rD^2 p / 4l \tag{1}$$

In Formula (1), r is the deflection amount of the workpiece, L is the distance between the center of the double balls, FG is the pressure in the hydraulic cylinder, D is the diameter parameter of the plunger, and P is the working pressure. The formula assumes that the pressure in the hydraulic cylinder is considered a concentrated force, while the spherical contact force is calculated according to the cosine law. During the calculation of this model, l = 4,190 mm, D = 1,240 mm, and P = 31 MPa were substituted into the formula for calculation, and the theoretical values calculated were compared with the simulation values obtained from the fluid–solid thermal coupling analysis, as shown in Figure9.

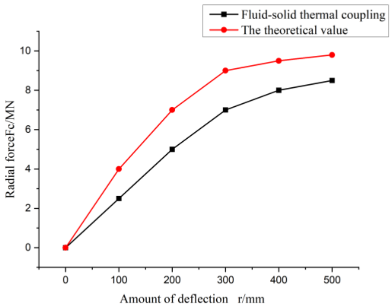


Figure 9: Radial force changes with deflection

As shown in the figure, for the amount of deflection change and fluid–solid–heat coupling, the theoretical value and the changes in radial force with partial loads increase, so the radial force is growing. The results show that fluid under the influence of thermal deformation increases the radial force of the guide sleeve. If you ignore the fluid and the influence of thermal deformation on the result, the calculated results tend to be conservative, so the ability to make use of calculation results in the actual safety factor is reduced. Therefore, the influence of heat and fluid on the structure must be considered in the design of hydraulic cylinders.

4.3. DMP discrete phase analysis

DMP uses the Lagrange method to track discrete particles. The fluid phase is treated as continuous, and discrete particles are calculated by tracking a large number of particles. With bubbles and particles through the flow field calculation, the flow field calculation in the process of particle or droplet trajectories is calculated under a special interval. The respective discrete phase can produce a flow field exchange of momentum, mass, and energy. According to the basic assumptions in the model calculations, assuming a discrete phase has a low-volume fraction, a volume fraction less than 10% usually allows a high-quality load. This model is suitable for the analysis of spray dryers, pulverized coal, liquid combustion, and full-load particle flow.

After thermal analysis, fluid analysis, and discrete phase setting were completed, DMP fluid–solid thermal coupling calculation was carried out, and the influence of fluid pressure and thermal deformation on the results is shown in Figure 10.

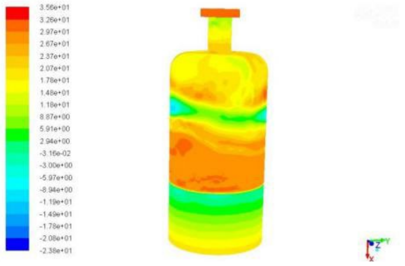


Figure 10: Fluid pressure distribution in the fluid–structure interaction

4.4. Hydraulic cylinder clearance optimization design

According to the above conclusions, under the same conditions, the hydraulic cylinder clearance is fit for different heat DMP fluid–structure coupling analyses. In the hydraulic cylinder clearance range of different values, as shown below, every 0.1 mm value to study the modeling will eventually result in statistics and make a graph.

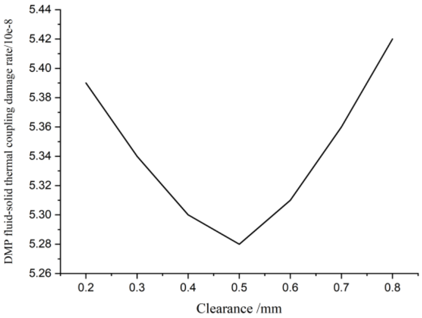


Figure 11: Clearance optimization diagram

As can be seen in Figure 11, if the clearance is too small, the damage rate will be large. Under the action of a partial load, the piston and cylinder are prone to contact dry friction, which leads to increased wear. As the gap increases, the damage rate decreases. When the gap is in the range of 0.4–0.6, the result is better. Then, as the gap increases, the damage rate also increases.

5. Conclusions

The temperature field has a significant influence on the hydraulic cylinder guide sleeve. The guide sleeve produces expansion deformation under thermal action, and the deformation causes an increase in plunger displacement. There is a large difference between the results of considering temperature fields and those of ignoring temperature fields, and the results of ignoring temperature fields will lead to smaller stress analysis results for the guide sleeve than the actual stress.

Under the action of a partial load, the internal pressure of the fluid leads to an increase in the radial force component. Under the action of fluid–structure coupling, the radial force component is larger than the radial force component of structural analysis, indicating that the internal pressure of the fluid increases the partial load effect. Therefore, in the design and verification analysis of hydraulic cylinder equipment, the safety factor should be properly redundant to ensure the safety performance of the structure.

Under the effect of the specific pollution particle diameter, the application of a DMP model was analyzed, and the interaction between particles was ignored. In the interaction of particles and the hydraulic cylinder, under this assumption, the results show that particles in the piston and hydraulic cylinders inside small gaps remain for a long time, so the particle pollution in this part of the plunger and the degree of wear and tear of the hydraulic cylinder are larger. Therefore, during the design process, the wear strength of this part is strengthened to increase the service life of the equipment.

The hydraulic cylinder clearance optimization analysis in a certain range shows that when the hydraulic cylinder clearance is between 0.4–0.6 mm, the hydraulic cylinder damage rate is the lowest under this condition.

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