Modeling and Jitter Suppression Analysis of a Lifting Multistage Hydraulic Cylinder

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Abstract. In view of the abnormal phenomena in the movement of the 4-stage hydraulic cylinder, this paper establishes the basic motion model of the multi-stage hydraulic cylinder by melting point nodal cavity method, and analyses the variation law of its external load. On this basis, the erection process of the multi-stage hydraulic cylinder is simulated and analyzed by AMESim, and it is found that the sudden change of pressure at the change of the stage will cause the vibration of the multi-stage. Found that the abnormal vibration of the third piston occurs during the retraction process of the hydraulic cylinder, which is caused by the insufficient guide distance of the 3 stage piston of the multi-stage hydraulic cylinder. The sealing conditions of the piston and the guide sleeve are improved by increasing the guide length of the piston appropriately, and the correctness of the improved scheme is verified by the way of simulation, that is, it can effectively suppress the vibration of the third piston. Vibration occurs during retraction. Some improvement suggestions are provided for vibration reduction of multi-stage hydraulic cylinder.

1. Introduction
Compared with single-stage hydraulic cylinder, multi-stage hydraulic cylinder can be installed in the situation of limited space and long travel requirement because of its long working stroke and shrinkable advantages, so it is widely used in large construction machinery, such as excavators, cranes and dump trucks. Most of the multi-stage hydraulic cylinders are driven and unloaded by hydraulic oil. The successive expansion of piston rods at all levels is achieved by collision with each other, which determines that the cylinder will have a greater impact in the process of limit. In addition, due to the influence of processing accuracy, load, wind resistance and other factors, the hydraulic cylinder in the
process of movement, especially in the process of unloading, will easily produce a greater degree of jitter, which will not only accompany the production of noise, but also cause serious multi-stage hydraulic cylinder head deformation, further aggravating the jitter. In order to ensure the stability of the motion process of the hydraulic cylinder and avoid potential safety hazards, it is necessary to model and simulate the motion process of the hydraulic cylinder.

For the research of multi-stage hydraulic cylinder, the paper [1] put forward the method of capacitive nodal cavity, and carries on the modeling analysis to the second-stage hydraulic cylinder; the paper [2] put forward the simulation analysis of multi-stage hydraulic cylinder using Multi-software collaborative technology; the papers [3, 4] specifically introduced a method of multi-stage hydraulic cylinder modeling-single-stage hydraulic cylinder cascade method, which provides a reference for the subsequent hydraulic simulation modeling. The paper [5] used AMESIM software to analyze and studied the erecting system of mine dump truck. Based on the appeal study, this paper takes the erecting cylinder of a certain rocket carrier vehicle as the research object. On the basis of the basic motion model and the change of external load, the erecting process is simulated and analyzed, and the abnormal jitter in the retraction process is simulated and improved, so as to provide some suggestions for reducing the vibration of the cylinder.

2. Basic Motion Model of Hydraulic Cylinder

This paper takes the 4-stage hydraulic cylinder of the erecting system of a certain rocket carrier vehicle as the research object. The cylinder is mainly composed of cylinder and 1, 2, 3 and 4 stage pistons which structure sketch is shown in Fig. 1.

![Figure 1. Structural sketch of 4-stage hydraulic cylinder.](image)

The diameters of each piston in the figure are $D_1$, $D_2$, $D_3$ and $D_4$, so the corresponding cross-sectional areas are $A_1 = \frac{\pi D_1^2}{4}$, $A_2 = \frac{\pi D_2^2}{4}$, $A_3 = \frac{\pi D_3^2}{4}$, $A_4 = \frac{\pi D_4^2}{4}$. For the multi-stage hydraulic cylinder, its internal pipe effect can be ignored, pistons at all levels can be regarded as hydraulic components connected with each cavity node, and the positive and negative cavities of the hydraulic cylinder can be calculated as the one cavities. Also the 1, 2, 3 and 4 stage cavities of the reverse cavities are interconnected, the four capacitive cavities can be regarded as one cavity, which is the reverse cavity. Assuming that the pressure of each point in the chamber is equal, it can be obtained from the continuity equation of hydrodynamics:

$$P(t) = \frac{E_0}{\Sigma V} \int_0^t \Sigma Q \, dt + P_0$$

(1)
In the formula, \( P(t) \) is the chamber pressure; \( \sum V \) is the total volume of the chamber; \( \sum Q \) is the total flow in and out of the chamber; \( E_0 \) is the volume elastic modulus of the oil; \( P_0 \) is the initial pressure of the oil.

For a hydraulic system, there must be clearance between pairs of motion, which will lead to leakage, which size of leakage has a great impact on the hydraulic system. Because the velocity of the whole movement process is small, it can be assumed that the leakage is laminar flow leakage. From this, we can obtained the leakage flow rate of piston in grades 1, 2, 3 and 4 stage pistons:

\[
Q_i = \frac{\gamma a_i d_i^4}{\rho 96vL} \Delta p
\]

\[
\gamma = \frac{2c}{D_i}
\]

In the formula, \( Q_i \) is the leakage flow rate of piston of the i stage; \( D_i \) is the piston diameter of the i stage; \( V \) is the motion viscosity of hydraulic oil; \( \rho \) is the density of hydraulic oil; \( L \) is gap length; \( \Delta p \) is the pressure difference between inside and outside piston, \( C \) is the radial clearance.

To sum up, the mathematical model of two-chamber pressure obtained by the method of capacitive cavity node [6] is as follows

\[
\begin{align*}
P &= \frac{E_0(Q_1 Q_2 Q_3 Q_4 - |v_{1p}|A_{a1} - |v_{21}|A_{a2} - |v_{32}|A_{a3} - |v_{43}|A_{a4})}{V + x_{1p}A_{a1} + x_{21}A_{a2} + x_{32}A_{a3} + x_{43}A_{a4}} \\
\hat{P} &= \frac{E_0(Q_1 Q_2 Q_3 Q_4 + |v_{1p}|A_{b1} + |v_{21}|A_{b2} + |v_{32}|A_{b3} + |v_{43}|A_{b4} - Q)}{V + (l_1 - x_{1p})A_{b1} + (l_2 - x_{21})A_{b2} + (l_3 - x_{32})A_{b3} + (l_4 - x_{43})A_{b4}}
\end{align*}
\]

In the formula, \( P \) and \( \hat{P} \) are the positive and negative pressure of the cylinder; \( Q \) and \( \hat{Q} \) are the flow into or out of the positive and negative cavities; \( v_{1p} \) and \( x_{2p} \) are the axial velocity and displacement of the 1 stage piston relative to the cylinder; \( v_{21} \) and \( x_{21} \) are the axial velocity and displacement of the 2 stage piston relative to the 1 stage piston; \( v_{32} \) and \( x_{32} \) are the axial velocity and displacement of the 3 stage piston relative to the 2 stage piston respectively; \( v_{43} \) and \( x_{43} \) are respectively the axial velocity and displacement of the piston piston with respect to the 4 stage piston with respect to the 4 stage piston with four pistons; \( V \) and \( V' \) are positive and reverse cavity volume; \( A_{a1}, A_{a2}, A_{a3} \) and \( A_{a4} \) are the positive cavity pressure acting area of the 1, 2, 3 and 4 stage piston; \( A_{b1}, A_{b2}, A_{b3} \) and \( A_{b4} \) are the reverse cavity pressure acting area of the 1, 2, 3 and 4 stage piston; \( l_1, l_2, l_3 \) and \( l_4 \) are the maximum displacement of the 1, 2, 3 and 4 stage piston; \( Q_1, Q_2, Q_3 \) and \( Q_4 \) are the leakage flow of piston of 1, 2, 3 and 4 stage piston.

3. Analysis of Cylinder External Load
The internal parameters of the hydraulic system are greatly influenced by the magnitude of external loads, especially the positive and negative intracavity pressure. The pressure of multi-stage hydraulic cylinder is almost entirely determined by external loads. On the premise of ignoring other external factors such as wind resistance and sudden change of external loads, this paper simplifies the stress process of multi-stage hydraulic cylinder in the erection stage, simplifies the stress of multi-stage hydraulic cylinder into a two-force bar, and simplifies the load into a rigid body, as shown in the Fig. 2, a force diagram at a certain position in the erection process [7]. The position of C is the center of gravity of the load, and the load and the bar head of the multi-stage hydraulic cylinder is articulated at A. The cylinder and the other end of the load are connected with the frame at O and B.
From the rigid body dynamics equation, the following equations can be established for the load:

\[ J\ddot{\theta}(t) = F(t)L_1 - GL_2 \]  

(5)

In the formula, \( J \) is the rotating inertia of load around point B; \( F(t) \) is the thrust of cylinder to load; \( \theta(t) \) is the angle between load around point B and horizontal plane; \( L_1 \) is the BM’s distance; \( L_2 \) is the BN’s distance. According to the triangular geometry, for Rt\( \Delta \)BCN:

\[ BN = BC \cos(\theta(t) + \beta) \]  

(6)

For Rt\( \Delta \)OBM:

\[ BM = OB \sin \angle BOM \]  

(7)

So:

\[ BM = OB \frac{AB \sin(\theta(t) + \alpha)}{OA} \]

(8)

\[ \cos(\theta(t) + \alpha) = \frac{AB^2 + OB^2 - OA^2}{2AB \cdot OB} \]  

(9)

According to the above formulas, the thrust of the oil cylinder to the load can be calculated as follows:

\[ |F(t)| = \frac{|J\ddot{\theta}(t)| + |G|BC \cos(\theta(t) + \beta)|OA}{AB \cdot OB \sin(\theta(t) + \alpha)} \]

(10)

With the increase of the length of the hydraulic cylinder, the load will gradually decrease. When extended to a certain length, the hydraulic cylinder will change from the original pressure to tension, and the force will gradually increase until the completion of the erection stage. As shown in Fig. 3, the positive value means pressure, while the negative value means tension. The main reason for this is the change of horizontal angle gamma of hydraulic cylinder. The relationship between horizontal angle gamma and extension length of 4-stage hydraulic cylinder is shown in Fig. 4.
4. Research on Simulation of erection stage

4.1. Multistage Hydraulic Cylinder Simulation Model
Used AMESim simulation software to analyze the process of hydraulic cylinder erection, however there’re no multi-stage hydraulic cylinder model which can be directly used in AMESIM’s own hydraulic model library, so the multi-stage hydraulic cylinder model can only be built by itself for HCD library. By decomposing the multi-stage hydraulic cylinder into single-stage cylinder cascade, we can decompose the multi-stage hydraulic cylinder into four single-stage cylinders according to the kinematic characteristics of the 4-stage hydraulic cylinder and the connection relationship between each chamber, as shown in Fig. 5. In the Fig. 5, the solid arrow points to indicate the direction of hydraulic oil flow in the main chamber, and the dotted arrow points to indicate the direction of hydraulic oil flow in the reverse chamber.

Figure 3. Relation Diagram of Extended Length and Load of 4-stage Hydraulic Cylinder.

Figure 4. Diagram of Relation Angle $\gamma$ and Extension Length of Hydraulic Cylinder.

Figure 5. Schematic diagram of 4-stage hydraulic cylinder decomposed into single-stage cylinder.
The simulation model of 4-stage cylinder is built by using the HDC Library of AMESim. As the sealing rubber rings are installed between pistons at all levels, as shown in Fig. 6. So, this paper considers which the seal is better, the influence of hydraulic oil leakage can be neglected in the course of movement. The results of construction are shown in Fig. 7.

![Figure 6. Piston diagram of a stage of 4-stage hydraulic cylinder.](image)

![Figure 7. Drawing of 4-stage Hydraulic Cylinder Model.](image)

4.2. Multistage Hydraulic Cylinder Simulation Model

The simulation results are shown in figs. 8-10. Fig. 8 is the displacement diagram of pistons at all levels of four-stage hydraulic cylinder in the erecting process. The piston at first moves simultaneously from the 1, 2, 3 and 4 stage piston. When the motion stroke reaches the limit position of the 1 stage piston, the bottom of the 1 stage piston collides with the end of the cylinder until it stops. Restrict the movement of the 1 stage piston, and then the 2, 3 and 4 stage piston continue to move. When the movement reaches the displacement limit position of the 2 stage piston, the 2 stage piston cylinder stops moving until the hydraulic cylinder is fully extended. Fig. 9 is the hydraulic pressure change chart in the positive and reverse chambers of the four-stage hydraulic cylinder in the erecting stage. At the beginning stage, with the entry of hydraulic oil, the pressure in the positive chamber increases until the load moves. Then the sudden change of cross-sectional area caused by the change of the stage causes the sudden change of the pressure, which will affect the smooth operation of the hydraulic system and often produce vibration. During the movement of the fourth-stage piston, the pressure of the positive chamber increases until the load moves. The direction of the load will change, and the hydraulic cylinder will change from the original pressure to tension, which will lead to the decrease of the positive chamber pressure and the increase of the reverse chamber pressure. Fig. 10 shows the velocity of the cylinder. In order to ensure the stability of the system, it is necessary to eliminate the sudden change of pressure caused by the change of multi-stage hydraulic cylinder.
5. Analysis of Abnormal Vibration of Cylinder in Retraction Process

The abnormal phenomena occurred in the retraction and debugging process of the fourth stage hydraulic cylinder. Vibration occurred in the range of about 300 mm in length when the third stage
piston was recovered, occasionally accompanied by abnormal noise. After that, the damage of the third stage piston dust ring was found in the inspection process.

5.1. Cause Analysis

(1) Unqualified fit clearance between piston and piston and guide sleeve

The matching clearance of piston-related parts of the 3 stage piston is 0.26mm and 0.31mm, and the design requirements are 0.056-0.37mm and 0.112-0.334mm. According to the comparison between the design requirements and the inspection values, the matching clearance meets the requirements, thus eliminating the problem of unqualified matching clearance between piston and piston and guide sleeve.

(2) Unqualified coaxiality of inner hole of rod barrel and supporting ring groove of guide sleeve

If the coaxiality between the inner wall of the second stage piston and the supporting ring groove of the guide sleeve is not qualified, it will inevitably lead to the close side of the third stage piston, which will cause additional radial loads on the motion of the third stage piston and cause vibration in motion. After testing, its coaxiality value is 0.05mm and the design requirement value is 0-0.075mm. Therefore, according to the comparison, the fit clearance meets the requirements.

(3) Short guide distance of piston rod

Check calculation of guide distance of 3 stage rod [9]: The minimum guide length of hydraulic cylinder should satisfy:

\[ H = S + 20 + D \div 2 = 287\text{mm} \]  \hspace{1cm} (11)

In the formula, \( H \) is the minimum guiding length; \( S \) is the maximum working stroke; \( D \) is the cylinder diameter. Through accounting, the actual guiding distance is 147.5mm < 287mm, which shows that the guiding does not meet the requirements.

5.2. Improvement measures

(1) Increase the guide length of the 3-stage guide sleeve, cancel the cap, and change the guide sleeve to integral threaded connection. Adding a supporting ring to increase the guiding area of guide sleeve and piston rod.

(2) Improve the minimum guide length of the third stage piston, increase the length of the spacer of 100mm in the third stage, and add two supporting rings in the inner wall of the spacer.

After the improvement of the above measures, the vibration phenomenon of the third stage piston in the retraction process has been significantly improved.

6. Conclusion

Based on the study of the 4-stage hydraulic cylinder, this paper establishes the basic mathematical model of motion and analyses the law of load variation. On this basis, AMESim is used to simulate and analyze the erection process, and it is known that the movement speed of the multi-stage hydraulic cylinder will change dramatically in the process of grading change. The causes of severe jitter of the 3 stage hydraulic cylinder in the process of retraction are analyzed, and the improvement measures are put forward. The results show that the vibration phenomenon has been effectively suppressed.

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