Modeling and Simulation of the Water Hydraulic Cylinder System Based on AMESim

Xiangzhou Deng¹, Kailuan Sun¹, Haiying Zhang¹, Yan Zhang¹ and Tengfei Li²
1 Zaozhuang Vocational College of Science and Technology, Tengzhou, 277599
2 Shandong University of Science and Technology, Qingdao, 266590
Email: 740712552@qq.com

Abstract. Pure water hydraulic is a green and pollution-free hydraulic technology, but the leakage in the cylinder makes its working efficiency greatly reduced. In this paper, a mathematical model of the water hydraulic cylinder has been established to analyze the factors of cylinder leakage. And a locking loop model with leakage module is established by AMESim software. Through simulation analysis, it is considered that the wall clearance of the water hydraulic cylinder is an important parameter affecting the leakage in the cylinder.

1. Introduction
In the new era, people's requirements for environmental protection are constantly improving, and water hydraulic transmission technology has been developed rapidly in the construction of national defense and some special economic fields. The hydraulic system of water medium has the advantages: wide source, no pollution, low price, quick response, small temperature rise, use safety and low cost of maintenance. It also has disadvantages such as heavy cavitation, strong corrosion and large leakage, etc. Which are the frontier subjects to be solved urgently in the fluid transmission technology.[1]

With the continuous development of science and technology, the dynamic characteristics of hydraulic system is more demanding than ever before, not only high efficiency and low energy consumption, but also high control precision, fast response and good stability. It analyzes and evaluates the whole system with computer simulation of hydraulic system, which can optimize the system with shorter design time and higher stability. AMESim is the preferred software for hydraulic transmission simulation because it has the advantages such as model building simply, fast graphic analysis, strong optimization function, etc. The water hydraulic cylinder is an indispensable part of the hydraulic system. It is significative to analyze the parameter which leads to large leakage with the modeling and simulation of water hydraulic cylinder.

2. Mathematical Modelling
Base on the power balance equation and flux continuum equation of two chambers, this paper establishes mathematical model of water hydraulic cylinder. [2] The physical model of water hydraulic cylinder is shown in Figure 1, and the direction of arrow is positive.
Ignoring the spring restoring force and the dry friction of the water hydraulic cylinder, the force balance equation of hydraulic cylinder is:

$$P_1S_1 - P_2S_2 = m\frac{d^2L}{dt^2} + b\frac{dL}{dt} + F_z$$ (1)

In Formula (1): $P_1$ is inlet pressure, the unit is MPa; $P_2$ is outlet pressure, the unit is MPa; $S_1$ is the area of piston with Non-rod chamber, the unit is m$^2$; $S_2$ is area of piston with rod cavity, the unit is m$^2$; $L$ is piston displacement, the unit is m; $m$ is the load mass and the unit is kg; $k$ is the elastic stiffness of load, the unit is N/m; $B$ is viscous damping coefficient, the unit is Ns/M; $F_z$ is the load force, the unit is N; $T$ is time, the unit is S.

According to the physical model in Figure 1, the flux continuum equation of the Non-rod chamber can be written:

$$Q_i = S_1\frac{dL}{dt} + C_1\frac{dP}{dt} + C_0(P_1 - P_2)$$ (2)

Water hydraulic cylinder input cavity C1 is:

$$C_i = \frac{V_01 + S_1L}{E}$$ (3)

In formula (4), $V01$ is the volume of Non-rod chamber of water hydraulic cylinder at the initial stage of piston, the unit is m$^3$; $E$ is water bulk elastic modulus, the unit is MPa; $C0$ is the internal leakage coefficient of water hydraulic cylinder, the unit is m$^3$ / (s·MPa). The Laplace transform of equations (1), (2), and (3) is obtained:

$$\frac{L(s)}{Q(s)} = \frac{1}{(\frac{mC_1}{ES_1} s^3 + \frac{bC_1}{ES_1} s^2 + bsC_0 + s)S_i}$$ (4)

The piston and the piston rod of the hydraulic cylinder are fixed connection, and there will be no leakage under the condition of qualified quality. However, the piston and cylinder wall are in the state of repeated friction when they are working, so long-term wear will inevitably lead to internal leakage. The leakage of water hydraulic system is much larger than that of oil hydraulic system, which expands the internal leakage coefficient by 100 times, C0 is 2.4x10$^{-9}$. Its Unit is m$^3$s$^{-1}$MPa$^{-1}$.

It is known that $\omega_n$ is the natural frequency of the load mass about the hydraulic cylinder, $\omega_n = \sqrt{\frac{ES_1}{mC_1}}$, the unit is rad / s. $\delta_n$ is the damping ratio of the hydraulic cylinder’s load mass, $\delta_n = \frac{C_1b^2}{4S_1^2Em}$ [4]. Substitute into (4), we obtain equation (5):
Ignoring the influence of the initial segment of laminar flow and fluid acceleration, the leakage rate of the oil pressure system is expressed as:

\[
L(s) = \frac{1}{Q(s)} \left( \frac{s^3}{\omega_n^2} + \frac{2\delta s^2}{\omega_n} + s \right) S_i
\]  

(5)

In formula (6), \(d\) is the inner diameter of the hydraulic cylinder, \(h\) is the height of the clearance between the piston and the cylinder wall, \(\Delta p\) is the pressure difference between the two ends of the clearance, \(\mu\) is the dynamic viscosity of the medium, and \(l\) is the length of the clearance.

The clearance length \(l\) and the inner diameter \(d\) of the hydraulic cylinder are constant. The leakage \(Q\) in the hydraulic cylinder is directly proportional to the differential pressure \(\Delta p\), and inversely proportional to the dynamic viscosity of the medium \(\mu\), and it is also related to the clearance height.

3. Software Modeling of Water Hydraulic Cylinder

The locking loop is a typical hydraulic system. This paper takes the locking loop as the research object and establishes the model with AMESim. As shown in Figure 2, the model mainly consists of two-way hydraulic lock, hydraulic cylinder and reversing valve.

![Figure 2. Locking loop model](image)

When locking, the motor presses the water medium into the directional valve. Through the two-way hydraulic lock, it flows into the non-rod chamber of the hydraulic cylinder to push the piston, so as to lock the hook lock. And the water medium flows back to the water tank through the two-way hydraulic lock and directional valve.

When releasing, water enters the reversing valve, then flows into the rod chamber of the hydraulic cylinder through the two-way hydraulic lock on the other side, and pushes the piston to release the hook lock.

At the same time, a leakage module is set in the water hydraulic cylinder to simulate the leakage in...
the locking water hydraulic cylinder. The height and length of the clearance between the piston and cylinder wall are simulated by the height and length of the leakage module’s clearance. The medium that flows through the clearance of the leakage module is the leakage rate in the hydraulic cylinder.

The medium of hydraulic system directly determines the characteristics of the system. The bulk elastic modulus \( E \) of water is 2100Mpa. The main external force of the piston in the hydraulic cylinder is the damping force of the medium. The viscous damping coefficient of water is related to the viscosity, it is about 425Ns/m, which is about 5%-10% of oil viscosity.

According to the actual situation, it sets parameters for the sub models of each component, as shown in Table 1:

| Parameter Name                      | Parameter Values | Unit   |
|-------------------------------------|------------------|--------|
| Motor speed                         | 1480             | r/min  |
| Rated capacity of pump              | 40               | cc/r   |
| Pressure of relief valve            | 250              | MPa    |
| Inner diameter of hydraulic cylinder| 60               | mm     |
| Piston rod diameter                 | 30               | mm     |
| Leakage module clearance           | 0.01             | mm     |
| Effective bulk modulus of water     | 1.24×10³         | MPa    |
| Viscous damping coefficient         | 425              | Ns/m   |
| Equivalent load mass                | 5                | kg     |

4. Simulation Analysis

4.1. Dynamic Simulation of the Water Hydraulic Cylinder System

The simulation time is 10s and the communication time is once every 0.1s. In order to obtain more data and verify the applicability of the model, several groups of displacement and velocity were input in the simulation to produce the time domain analysis diagram of displacement and velocity of water hydraulic cylinder piston. As shown in figures 3 and 4:

![Figure 3. Time domain analysis of displacement](image)

![Figure 4. Time domain analysis of velocity](image)

As can be seen from the figure, the hydraulic cylinder has been working in place at 0.4s, it has locked the hook lock. After 5S, it starts to release the hook lock. After 0.4s, the action was completed. The whole process is very fast and stable, which is consistent with the actual working situation.
As shown in the figure, the pressure difference at both ends of the water hydraulic cylinder is basically consistent with the leakage curve and proportional.

There is also a certain relationship between the leakage of the medium and the trajectory of the piston. When the piston moves to the limit position after 0.4s, the maximum change of the leakage rate occurs. When the pressure on the left side of the piston is greater than the right side, the medium leaks from the left side to the right side, and when the pressure difference between the two sides goes to 0, the leakage also becomes 0. Under the same conditions, the proportional coefficient between the leakage in the water hydraulic cylinder and the pressure difference between the two ends of the cylinder wall gap calculated by equation (7) is basically consistent with the simulation results, which verifies the mathematical model.

4.2. Influence of Leakage Module Clearance on Internal Leakage

According to the theoretical formula of internal leakage, the leakage in the hydraulic cylinder is related to the clearance of the leakage module. Using the batch function of AMESim software, the clearance of the leakage module was set as 0.01 mm, 0.03 mm and 0.05 mm respectively, to produce the time-domain diagram of the leakage rate and the clearance of the leakage module.

As can be seen from the figure, with the continuous increase of leakage module clearance, the extreme value of leakage in the water hydraulic cylinder increases in coefficient. According to the equation (7), the leakage is directly proportional to h3, which is similar to the simulation results. When the clearance h=0.05mm, the leakage in the water hydraulic cylinder is very large that it can not work normally. The piston only runs one stroke within 10s, and the leakage will be remained unchanged after 5s.
5. Conclusion
In this paper, it combined with the internal characteristics of water hydraulic cylinder to deduce the mathematical model of its dynamic characteristics. A leakage module was added to the physical model of water hydraulic cylinder to solve the serious leakage problem. The classic locking loop was simulated by AMESim, and the following conclusions were drawn:
1) The leakage module is added into the locking circuit model of water hydraulic cylinder built by AMESim to simulate the internal leakage of water hydraulic cylinder. The operation is smooth and has good stability. The linear relationship between the input and output variables of the system was basically consistent with the theoretical calculation of the mathematical model.
2) The clearance between the piston and the cylinder wall of the water hydraulic cylinder is an important parameter that affects the leakage in the cylinder. When the clearance reaches a certain value, it will affect the normal operation of the hydraulic cylinder.
Next, we hope to continue to do some work about the manufacturing process of the piston in the water hydraulic cylinder and CAE parameter optimization.

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7. References
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