Research on pressure pulsation of piling hammer hydraulic system based on AMESim

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Abstract. The mathematical model of pressure pulsation of piling hammer hydraulic system is established, and the results of the pressure pulsation of piling hammer hydraulic system are analyzed by AMESim. The results show that only the accumulator with the optimal pressure and capacity can effectively absorb the pressure pulsation and ensure the efficiency of the piling hammer hydraulic system. Through mathematical model and AMESim simulation analysis, it provides a certain theoretical research basis for the study of pressure pulsation in hydraulic system of piling hammer.

1. Introduction
With the development of society, hydraulic systems are developing toward high pressure, high flow, high speed and accuracy, in which the problem of pressure pulsation is receiving more and more attention from researchers. Due to the pulsation of the hydraulic pump, the influence of piping, reversing the direction of the reversing valve, etc., the flow rate in the hydraulic system produces instantaneous changes, thus producing flow pulsation. Flow pulsation inevitably causes pressure pulsation, generates vibration and noise, adversely affects the hydraulic system, and reduces its service life [1].

In recent years, marine resources development and wind power utilization and other marine engineering have developed at a high speed, and in order to adapt to the increasingly high diameter and depth requirements of marine engineering pile foundations, the percussion force, power, and efficiency of offshore operation piling hammers have become more and more demanding [2]. At the same time, the working pressure and flow rate of the hydraulic system supporting the offshore operation piling hammer are also getting larger and larger, and the impact of pressure pulsation is also increasing. How to reduce the hydraulic pulsation shock and improve the efficiency and service life of the hydraulic system has become one of the key concerns of relevant domestic and foreign researchers. Shen et al. made a detailed analysis of the working cycle of the hydraulic system of NH-type hydraulic pile-driving hammer [3]. Dong and Cao et al. used accumulators to reduce the hydraulic shock in the hydraulic system [4, 5]. Cao also reduced the hydraulic pulsation shock by reducing the hydraulic pump displacement. In addition, Ji and Fu reduced hydraulic pulsation shocks by optimizing the control strategy [6].

In this paper, the pressure pulsation generation mechanism of the piling hammer hydraulic system is studied, and the mathematical models of hydraulic pipe, pressure fluctuation caused by switching valve and accumulator are established to analyze the pulsating shock generation mechanism and pulsating shock absorption mechanism of the hydraulic system. AMESim software is used for simulation analysis.
to verify the absorption of pulsating shock by the accumulator, and to provide the corresponding theoretical basis for the subsequent research and application of offshore pile driving hammer.

2. Pressure pulsation mathematical model

The hydraulic circuit of the offshore piling hammer is not complicated, mainly consisting of inlet and return switching valves, which control the application of hydraulic cylinders and thus drive the up and down movement of the hammer core of offshore operation piling hammer. During the entire work cycle, the main reasons for the pressure pulsation are the dynamic characteristics of the pipe and the frequent switching of the switching valve, etc. This paper will carry out the relevant theoretical analysis for these two points.

![Figure 1. Pipe dynamic model](image)

Due to the long length of the hydraulic pipe, the losses caused by the pipe, the flow fluctuations caused by pressure fluctuations, and the pressure fluctuations caused by flow fluctuations will have a large impact on the hydraulic system during the lifting of the hammer core. Fig. 1 shows the dynamic model of pipe, where \( l_T, A_T, d_T \) are the length, effective area and inner diameter of the pipe; \( p_1, Q_1, p_2, Q_2 \) are the pressure and flow rate of the inlet and outlet of the pipeline respectively; \( p, Q \) are the pressure and flow rate at any point of the pipe respectively. In order to simplify the calculation process, let the pressure and flow rate are only related to the coordinates \( x \) and time \( t \), that is, the pressure and flow rate are expressed as \( p(x,t) \) and \( Q(x,t) \). The force balance equation and the flow continuity equation of the unit hydraulic column at the coordinates can be obtained as

\[
\rho A_t \frac{d}{dt} \left( \frac{Q(x,t)}{A_t} \right) = p(x,t)A_t - \left[ p(x,t)A_t + \frac{\partial p(x,t)}{\partial x} dx A_t \right] - \frac{128 \mu dx}{\pi d_T^4} A_t Q(x,t) \quad (1)
\]

\[
Q(x,t) - \left[ Q(x,t) + \frac{\partial Q(x,t)}{\partial x} dx \right] = \frac{A_t}{K} dx \frac{\partial p(x,t)}{\partial t}, \quad (2)
\]

Where \( \rho \) represents the density of hydraulic fluid, \( \mu \) represents the hydraulic fluid dynamic viscosity and \( K \) represents the equivalent bulk modulus of hydraulic oil.

Within the Laplace variation, partial derivative, and bringing in the pressure and flow conditions at the inlet of the line, the pressure and flow expressions at the outlet of the line can be obtained as

\[
p_2(s) = p_1(s) \cosh(\gamma(s)l_T) - Z_0(s)Q_1(s) \sinh(\gamma(s)l_T), \quad p_2(s) = Q_1(s) \cosh(\gamma(s)l_T) - 1/Z_0(s) p_1(s) \sinh(\gamma(s)l_T), \quad (3)
\]

\[
Q_2(s) = Q_1(s) \cosh(\gamma(s)l_T) - 1/Z_0(s) p_1(s) \sinh(\gamma(s)l_T), \quad (4)
\]

Where \( \gamma(s) \) is the propagation operator, \( \gamma(s) = s(1 + \frac{32\mu}{\rho d_T^2 s^2})^{\frac{1}{2}} l_T / \sqrt{K / \rho} \). \( Z_0(s) \) is the characteristic damping, \( Z_0(s) = \frac{4\rho \sqrt{K / \rho}}{\pi d_T^3} (1 + \frac{32\mu}{\rho d_T^2 s^2})^{\frac{1}{2}}. \)
It can be seen from Equations (3) and (4) that the pressure and flow pulsation of hydraulic pipe are mainly affected by the length of pipeline, effective area and oil related characteristics. When the disturbance frequency is close to the relevant frequency, it will produce a large fluctuation impact. And pressure fluctuations and flow fluctuations will interact with each other, further increasing the impact of pulsation impact. The generation of this pulsation is difficult to calculate directly through numerical methods, often using computer software to assist in obtaining its corresponding time-domain response characteristics.

In addition, the frequent opening and closing of the switching valve is also the main reason for the pressure pulsation. When the offshore operation piling hammer is lifted to the highest point, the switch valve of the inlet circuit is suddenly closed, causing a drastic change in the flow rate of the hydraulic oil in the inlet circuit, which is influenced by inertia, the hydraulic oil will produce a corresponding impact, which is expressed as a drastic change in pressure. In general, the first wave pressure change of this type of pressure pulsating is the largest, and according to the theorem of conservation of energy, there is equal kinetic and elastic potential energy of hydraulic fluid [8], which is

$$\rho A \frac{v^2}{2} = A \frac{\Delta p^2}{2K}, \quad (5)$$

Where $v$ is the initial velocity of hydraulic oil. Equations (5) gives the expression for the maximum pressure fluctuation as

$$\Delta p = \rho v \sqrt{K / \rho} \quad (6)$$

The pressure change is proportional to the initial velocity of hydraulic oil, and this pressure pulsation is continuously transmitted and reflected in the pipe until the energy of this pulsation is completely exhausted. In order to ensure the working efficiency of the piling hammer for offshore operation, its lifting and dropping time is generally short, so the hydraulic oil velocity in its inlet circuit is fast. In the actual working process, it will produce pressure pulsation with stable frequency for a long time, which adversely affects the service life of the switching valve.

3. Modeling and simulation based on AMESim

Within the parts library in AMESim software, the basic hydraulic circuit simulation model of the piling hammer for offshore operation is built. The basic parameters, such as the flow rate of the hydraulic system is set to 5400L/min and the working pressure is set to 33Mpa. The simulation result of pressure fluctuation at the switching valve is shown in Fig. 2.

![Figure 2. Pressure at the switching valve](image)

From Fig. 2, in 1.6 s and 3.3 s, due to the sudden closing of the switching valve, a pressure pulsation about 2Mpa is generated and decreases rapidly. This pressure pulsation is consumed by the switching valve and pipe together, which will have a negative impact on the service life of the system. In 1.6 s and 3.3 s, a pressure pulsation is caused by the opening of the switching valve, which produces a
phenomenon of local unloading. This pressure pulsation is less damaging to the system. For most of the rest of the time, the main cause of the pressure pulsation is the dynamic response of the pipe. Especially in the start-up phase, the pressure pulsation lasts for a long time, the pulsation amplitude is larger, and the corresponding pulsation time is longer. Compared with the pulsation generated by the switching valve, the impact is weaker, but still produces a certain impact. The main source of this pressure pulsation is the load end, the piling hammer lifting process cannot maintain a stable and uniform velocity, thus producing a certain pressure and flow pulsation. Due to the long hydraulic pipeline, the dynamic characteristics of the pipe will produce continuous pressure and flow pulsation. This pulsation will be stabilized after a long period of time, but the pulsation cannot be completely restored to smoothness by the working frequency of the piling hammer in offshore operation, and it enters the next working cycle before entering the stable state.

To alleviate the pressure pulsation, an accumulator is installed in front of the switching valve. The gas pre-charge pressure of the accumulator is adjusted to 20MPa, 25MPa and 30MPa respectively, and the volume is adjusted to 250L. The pressure simulation curve for the same position is shown in Fig. 3.

![Figure 3. Pressure with different gas pre-charge pressures](image)

From Fig. 2 and Fig. 3, it can be seen that the pressure pulsation of the hydraulic system changed significantly after the installation of the accumulator. Gas pre-charge pressure of 30MPa, the absorption of pressure pulsation is not as good as the gas pre-charge pressure of 20MPa and 25MPa. Compared with the gas pre-charge pressure of 25MPa, the absorption effect of 20MPa is similar, but the response time of 20MPa increased significantly. In summary, if the gas pre-charge pressure is too high, the absorption effect of the accumulator on the pressure pulsating is not good, and if the gas pre-charge pressure is too small, the response time of the system increases.

The gas pre-charge pressure of the accumulator is adjusted to 25MPa, and the volume is adjusted to 250L, 500L and 750L respectively. The pressure simulation curve for the same position is shown in Fig. 4.

![Figure 4. Pressure with different volumes](image)
From Fig. 4, the larger the volume of the accumulator, the better the absorption of the pressure pulsating, while the longer the system response time. The installation of the accumulator can be regarded as changing the inherent frequency of the pipe, making it far away from the working frequency of the piling hammer for offshore operation, which makes the original pressure pulsation of the pipe greatly reduced and absorbs the pressure pulsation generated by the switching valve at the same time.

4. Conclusion
In this paper, a theoretical analysis of the mechanism of pressure pulsation in the hydraulic system of piling hammer for offshore operation is carried out, a relevant mathematical model is constructed, and AMESim is used for simulation analysis. The following conclusions are mainly obtained:

①The main sources of pressure pulsation in offshore piling hammers include the frequent opening and closing of switching valves and the influence of dynamic characteristics of hydraulic pipe. The pressure pulsation generated by the switching valve is short and impactful, but the pressure fluctuation is small. The pressure pulsation generated by the dynamic characteristics of the hydraulic pipe is long and the pressure fluctuation is large. Both will affect the service life of the hydraulic system.

②Pressure pulsation can be mitigated by installing an accumulator. But according to the characteristics of the hydraulic system, the pre-charge pressure and volume of the accumulator should be selected correctly to ensure that the system can effectively absorb the pressure pulsation and have better response characteristics. Thus, the life and reliability of the hydraulic components can be improved.

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