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Cushioning structure optimization of excavator arm cylinder

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ABSTRACT

Severe impact and vibration may appear when a high-pressure cylinder is working. So in order to slow down the piston and prevent the damage to the cylinder, cushioning structures located in the end or head of a high-pressure cylinder should be optimized. In this work, the working principle of arm cylinder cushioning structures was analyzed, and multi-domain simulation models (especially cushioning model of the arm cylinder) of excavator were built on *SimulationX* platform. Finally, tests were carried out on a 6 T excavator under typical working conditions to verify the model. Cushioning pressure and piston velocity were taken as the main evaluation indexes based on the model. The variable-controlling approach was adopted to test the sensitivity and to find out the optimal values of some key cushioning structure parameters individually. The results showed that the oblique planes on the outer surface of cushioning bush play the most important role in the cushioning of cylinder piston-side chamber, as for rod-side chamber, the throttling orifices on the cylinder cover affect the cushioning performance greatly. The angle of oblique planes of cushioning bush in piston-side chamber was set at 2.5°. Three oblique planes for piston-side cushioning bush have been recommended.

1. Introduction

As one of the most important construction machineries, hydraulic excavator is widely used in mines, road building, as well as civil and military construction due to its high efficiency and multifunction [1,2]. Furthermore, service and operation requirements for hydraulic excavator are becoming more demanding; thus, the reliability of hydraulic components is a matter of urgent concern. This can be achieved by applying electronic processing technology to fine finish mechanical components [3]. However, compared to complex and less reliable electrical system, mechanical structure optimization tends to be more reliable and costless. To reduce the hydraulic impact and protect the hydraulic system, cushioning system like hydraulic shock absorber, has been studied a lot in recent years. Milecki and Hauke [4] proposed a semi-active shock absorber with magneto-rheological fluid, a spring and electronic controller, which was capable of controlling the stopping process of moving objects. Thus, a solution was proposed to adjust the braking force automatically. However, this kind of absorber is large and costly [5,6].

The most common cushioning system for hydraulic cylinder, despite the new technologies, is composed of some pressure and circuit control valves. Alternatively, a stroke end-cushioning device, which is simple to construct, may be used [3]. Stroke end-cushioning device is used in hydraulic cylinders moving with high inertial loads and/or moving at high speed. Since a stroke end-cushioning device is used to reduce shocks against the cylinder head, it must reduce the kinetic energy acquired by the piston-rod-load set during its operation.

The stroke end-cushioning device aims to exert a cushioning effect by restricting oil flow from a chamber, increasing this chamber oil pressure, and hydraulically braking the motion of the piston [7]. To obtain desirable cushioning performance, the structure parameters of stroke end-cushioning devices are in desperate need of optimization.

Direct calculation methods, general optimal algorithms, or improved optimal algorithms can be used in optimization [8,9]. The direct way is seriously influenced by optimal sequence, and the general optimal algorithm may not achieve the feasible solution or converge at local optimum in restricted periods or iteration times [10]. With the development of computer technology, computer simulation becomes an increasingly important factor for investigating dynamic characteristics of hydraulic elements and systems [11]. Sun and Jing [12] built a model in Matlab/Simulink environment to check energy saving capacity of PHHL with proposed configurations and energy control strategy. Shi et al. [13] carried out 1D simulation on AMESim platform to confirm the proposed energy saving strategy of cutterhead hydraulic drive system of shield tunneling machine. Ho and Ahn [14] presented a hydraulic energy-regenerative system and used simulation method to evaluate its validity. Xu et al. [15] presented a model to evaluate and optimize the safety brake performance of hydraulic lift system. Xie et al. [16] built a model based on co-simulation platform to conduct analysis on light passenger car with dual state CVT under typical working conditions. Reineh and Pelosi [17] investigated the physical behavior of an advanced automotive racing shock absorber, and studied the influence

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of each single component on the shock absorber static and dynamic performance with a simulation software-AMESim. Zhang et al. [18] built a model with *SimulationX* to analyze energy saving strategies of the loader working device. Although the researches referred above are innovative pioneers in this area, their simulations are either one-dimensional or two-dimensional. Hence, 3D mechanical parts are not being fully considered, and few researchers have tried to apply simulation method to optimize the mechanical–hydraulic structures.

In this paper, a 6 T excavator arm cylinder was taken as the research object, wherein a set of new cushioning units is taken into account. The new design was completed in collaboration with a company based on its former designs. The problem is that even though the whole new cushioning system is applied, the oil pressure in the cylinder can still reach up to 30–40 MPa under severer working circumstance, so the cushioning structures must be optimized to reduce hydraulic shock caused by such high pressure oil. This paper proposes a special simulation model of arm cylinder used in an excavator based on *SimulationX*, and it builds a multi-domain model of excavator attachment. In this model, 3D mechanical parts are seamlessly integrated with 1D mechanical and hydraulic part in order to simulate close to actual situation.

This paper is organized as follows. Basic theories and working principles of cylinder stroke end-cushioning units are presented in Section 2. Modeling in *SimulationX* platform is presented in Section 3. The results of the validation of simulation model are presented in Section 4. Parameter optimization of cushioning structures in the cylinder based on the verified model is presented in Section 5, and conclusions are given in Section 6.

2. Basic theories and working principles of cylinder cushioning units

The 3D model of excavator high-pressure arm cylinder is illustrated in Fig. 1. Generally, a hydraulic cylinder should include the following components: cylinder tube, piston, piston rod, cylinder cover, exhaust device, various rings and cushioning units.

2.1. Rod-side chamber

Cushioning units of arm cylinder rod-side chamber are shown in Fig. 2. The respective fit relations between floating cushioning bush and piston rod, cylinder cover are all clearance fit, which allow the floating cushioning bush to do tiny shifts along the rod radially. Throttling orifices in the cylinder cover are one of the important cushioning units for the cushioning of rod-side chamber. When cushioning bush enters into the gap between the rod and the cover, significant cushioning effects can be obtained. The floating cushioning bush plays a major role in the cushioning process of the rod-side chamber. Three evenly distributed oblique planes with angle of 0.6° are processed on the external surface of the cushioning bush, which is one of the key working areas in the cushioning process. The left end of the cushioning bush is a fine finishing surface, with a chamfer angle of 10°. Two evenly distributed radial oil-through grooves are designed on the right end to allow oil to pass through.

In non-cushioning stroke, the cushioning bush stays in a floating state and is not in effect. When the oil pressure begins to rise due to the cushioning effect, the cushioning bush will center and move to the left automatically under the action of pressure differential to cut off the annular gap between the cushioning bush and piston rod. At this point, there are two oil paths, as marked with dash-dotted line in Fig. 2. One path shows that oil passes through the throttle orifices and flows out, i.e., path A. The other path shows that the oil passes through the gap between cushioning bush and the cylinder cover and flows out, i.e., path B.

When the cushioning bush starts to enter into the cover, oil in the rod-side chamber can still be discharged through the throttling orifices and the gap between the cushioning bush and the cover. However, the gap is reducing dramatically. Thus, there is a sudden pressure rise due to the oil accumulation in the rod-side chamber, which generates resistant force against the piston to slow it down. Furthermore, the effect of three evenly distributed oblique planes on the external surface of the cushioning bush decreases throttling area with movement of piston rod, so the pressure in the rod-side chamber increases gradually and steady cushioning effects can be implemented. After the cylinder cover fully blocks the oblique planes, only throttling orifices are in action, i.e., only path A is left to discharge oil.

For path A, the throttling orifices play a major role. Fig. 3 presents the ideal model of short orifice throttling.

The volume flow through the throttling orifice can be described with the following formula:

$$Q = a_D A_0 \sqrt{\frac{2}{\rho}\Delta p} \tag{1}$$

where Q is the volume flow, a_D is the flow coefficient, A_0 is the cross section area of the orifice, Δp is the oil pressure differential, and ρ the is oil density.

The flow coefficient a_D can be obtained with formula (2):

$$a_D = \sqrt{\frac{1}{\varsigma}} \tag{2}$$

where, ς is the pressure loss coefficient for circular orifice, that can be evaluated by formula (3):

$$\varsigma = \frac{1}{\mu} - \frac{A_0}{A_1} \tag{3}$$

where, μ is the contraction coefficient, and A_1 is the upstream cross section area.

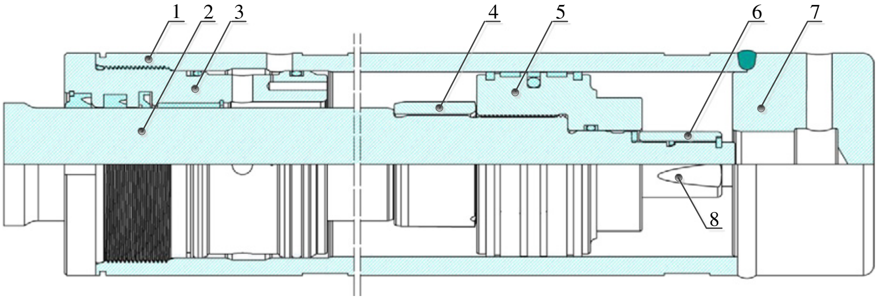

Fig. 1. Main components of excavator high-pressure arm cylinder: 1–cylinder tube, 2–piston rod, 3–cylinder cover, 4–floating cushioning bush, 5–piston, 6–floating cushioning bush, 7–cylinder head, and 8–cushioning ring.