A STUDY ON PRESSURE SURGE ACCOMPANIED BY REPEATED VALVE OPERATION IN OIL HYDRAULIC PIPELINE

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ABSTRACT

In a large scale oil hydraulic system having repeatedly operated actuator, such as a large scale forging press, pressure surges often occur due to the recombination of oil column in a return line attached to the downstream side of a directional control valve. Especially, the pressure surges appear very severe ones at a certain valve operating frequency. These pressure surges restrict the operating frequency of the hydraulic system. But there are few reports about the above mentioned phenomenon.

In this study, therefore, the authors investigate the exact reason why such severe pressure surges occur at a certain range of valve operating frequency. And for that purpose, the relationship between pressure surges and valve operating frequency is studied by experiments and numerical computations.

KEYWORDS

Hydraulic Power System,
Surge Pressure, Transient Flow,
Repeatedly Operated Valve

NOMENCLATURE

A : sectional area of pipe
a : wave speed
B : $a/(gA)$

C^*, C : characteristics line
D : inside diameter of the pipe
f : coefficient of frictional loss in a pipe
g : gravitational acceleration
H : pressure head
 h_f : headloss due to fluid friction per unit length of the pipe
L : length of pipe
N : number of reaches a pipe subdivided for computation
 N_B : moles of gas in a cavity
 P_o : pressure at high pressure reservoir
 P_r : pressure at low pressure reservoir
Q : flow rate
T : absolute temperature
t : time
 Δt : increment of time
 t_1, t_2 : time interval defined in Fig.2
: flow velocity
 V_o : steady flow velocity
W : volume of cavity
x : distance along the pipe
 Δx : distance interval on the pipe ($\Delta x = L/N$)
 γ : specific gravity of fluid
 ψ : ratio of interpolation
subscripts
A, B, C, D, P: grid points

INTRODUCTION

In a large scale oil hydraulic system having repeatedly operated actuator, such as a large scale forging press, severe pressure surges often occur due to the recombination of oil column separated in the return line attached to the downstream side of a directional control valve. Especially when the valve operation frequency exceeds a certain limit the pressure surges appear more significant ones with a crushing sound. So, in a large scale oil hydraulic system as a large free forging press the operation frequency of the directional control valve is generally set to a certain low values which is decided from field engineers' experiences. Nevertheless the generation mechanism of the pressure surges is not yet clarified.

And also, it is known by field engineers' informations and authors' preparatory experiment that the pressure surges are influenced very much by the variation of valve operation frequency. Therefore, the authors investigate the relationship between the valve operation frequency and the pressure surges by experiment and numerical computation. The object of experimental pipeline is a model pipeline simplifies a return line of a large scale forging press. By consideration of experimental results and computation results, we try to explain more rationally the generation mechanism of the surge pressure.

EXPERIMENTAL APPARATUS
AND EXPERIMENTAL PROCEDURE

Fig.1 shows a simplified pipe model of a return line of a large scale oil hydraulic forging press. Experiment in this study applies to the pipe model which has simple

Fig.1 Pipe model for experiment and computation

boundary conditions and smaller dimensions compared to a real equipment but can similarly describe physical aspects of the real equipment. Schematic diagram of the experimental apparatus is shown in Fig.2. Accumulators are used as constant pressure reservoirs, and pressure setting is done with relief valves. The pipe used in experiment is copper pipe which has 12.7mm in inside diameter and 25m in total length. A directional control valve is installed at a distance of 5m from the upstream end of the pipe. The pressure variations are measured using strain gauge type pressure transducers set at the positions of 5m and 15m from the upstream end of the pipeline. A commercial hydraulic oil is used, and the kinematic viscosity and specific gravity of it are 45.5cSt at 45°C and 0.866 at 25°C respectively. The directional control valve employed is a double acting solenoid spring offset type, which can operate repeatedly according to the timing as shown in Fig. 3. For this purpose, the authors specially designed and made a valve controller which generated periodic on-off control signals with arbitrary duration time.

The experiment is started under steady flow state which is established by opening the valve fully and setting the pressure at both accumulators. The experiment is carried out by operating the valve

Fig.2 Schematic diagram of experimental apparatus

Fig.3 Valve operating state

using the valve controller. The pressure variations are recorded on a X-Y plotter through a dual-channel memoryscope. Also, the duration time at opened and closed state of the valve are measured on the pressure records.

NUMERICAL ANALYSIS

The equations of motion and continuity for one-dimensional flow in horizontal pipe are given as follows.

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + g \frac{\partial H}{\partial x} + g \cdot h_f = 0 \quad (1)$$

$$\frac{\partial H}{\partial t} + V \frac{\partial H}{\partial x} + \frac{a^2}{g} \frac{\partial V}{\partial x} = 0 \quad (2)$$

These equations can be transformed into a pair of total differential equations by characteristics method. And if taking the difference on characteristics lines C^+ and C^- , we get the following finite difference equations.

$$C^+ : H_P = C_P - B \cdot Q_P \quad (3)$$

$$C^- : H_P = C_M + B \cdot Q_P \quad (4)$$

where $C_P = H_A + B \cdot Q_A - h_f$
 $C_M = H_B - B \cdot Q_B + h_f$

Since the flow pattern in the experiment is laminar, the headloss per unit length of a pipe is computed considering the effects of frequency dependent friction in unsteady laminar flow.⁽¹⁾ Also, the volume of the cavity during liquid column separation is computed by the gas discrete model⁽²⁾. The boundary condition of the directional control valve is shown in Fig.4. During the valve operating, the flow rate across the valve is described as following equation.

$$Q_{P1} = Q_{P2} = \text{sign}(C_{P1} - C_{M2}) \frac{Q_0}{\sqrt{\Delta H_0}} \sqrt{|H_{P1} - H_{P2}|} \quad (5)$$

Fig.4 Boundary condition of the directional control valve

Where, H_0 and Q_0 are steady head loss and steady flow rate across the valve at fully open valve state, and subscripts 1,2 indicate the upstream and downstream pipe. So, pressure head and flow rate just after the valve can be computed by solving equation (3), (4) and (5) simultaneously.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Fig.5 illustrates the records of the pressure waves taken just after the directional valve ($x = 5\text{m}$). Fig.5.① is the case that t_2 is comparatively long, and t_1 is longer than t_2 , where t_1 and t_2 is defined in Fig.3. Fig.5.②,③ and ④ are the case that t_2 is gradually shortened under the same physical conditions with Fig.5.①.

Fig.5 shows that pressure surges occur according to the oil column recombination, and in certain operation frequency the pressure surges appear very severe ones with crushing noise. Fig.5.② is one example of such cases. From these experimental results, it is said that the magnitude of pressure surge becomes very big one when the valve opens during the duration of cavity. Fig.5.③ is the case that t_1 is adjusted to approximately equivalent value with t_2 . Fig.5.④ shows that the pressure waves have comparatively good reproducibility. Also, it is known that the computed results from characteristics method show good agreements with experimental results.

Now, comparing Fig.5.③ with Fig.5.④, it is said that very severe pressure surges appear at Fig.5.④ although the valves open during the duration of cavity at both cases. So, in order to investigate the reason for the

Fig.5 Comparison of experimental results with computed results
($P_0 = 1.15$ MPa abs, $P_r = 0.3$ MPa abs, $V_0 = 2.12$ m/s, $x = 5$ m).

Fig.6 Computed values of pressure ①, mean velocity ② and cavity volume ③
(the same physical conditions with Fig.5(a) ③, $x = 5$ m)

difference, we consider about the computed results of the variation of pressure, mean velocity and cavity volume shown in Fig.6. Fig.6(a),(b) is obtained at the same physical conditions with Fig.5.③, ④ respectively. From Fig.6, it is explained clearly that the pressure surges are affected considerably by the variation rate of cavity volume and mean velocity.

CONCLUSIONS

The mechanism of the generation of severe pressure surge in the pipeline with repeatedly operated valve in a large scale oil hydraulic equipment was investigated experimentally and numerically, using a simplified pipe model.

Severe pressure surges were observed when the repeatedly operated valve opened before the first recombination of the cavity. The mechanism of severe pressure surge was explained rationally by consideration on the variation rate of pressure, mean velocity and

cavity volume. And the surge pressure could be predicted with good agreement by computation with the method of characteristics.

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