1A1-2

Proceedings of the 6th JFPS International
Symposium on Fluid Power, TSUKUBA 2005
November 7-10, 2005

APPLICATION OF A PRESSURE INTENSIFIER USING OIL HAMMER TO A HYDRAULIC CYLINDER OF A CONSTRUCTION MACHINE

Katsumasa SUZUKI, Kentarou YOKOYAMA ,
Yosuke ENDO and Yasumichi SHIBATA
Department of Mechanical Systems Engineering,
Musashi Institute of Technology
1-28-1 Tamazutsumi Setagaya-ku Tokyo, 158-8577 Japan
E-mail: ksuzuki@sc.musashi-tech.ac.jp

ABSTRACT

The active utilization of the pressure rise phenomenon of an oil hammer and a new type of hydraulic pressure intensifier using an oil hammer were proposed and developed. In this research, an application of this intensifier to pressure intensification in a hydraulic cylinder of a construction machine is studied through experimentation and simulation.

High pressure is generated when the fluid flow through the pipeline is shut quickly by the solenoid operated valve at the downstream end. If the fluid is taken out through the check valve when the pressure is high, much higher-pressure fluid than the supply is obtained. A vessel is used as a model of a hydraulic cylinder without displacement. The pressure of the vessel is intensified. The necessary pressure level is thought to be around 30MPa. We develop a block diagram for the simulation considering the pipeline dynamics.

Key words:
Pipeline, Water Hammer, Oil Hammer, Intensifier, Hydraulic Cylinder

NOMENCLATURE

a : sonic velocity in fluid （＝1.26×10^{3}m/s）
A : pipeline area
A_3 : line cross sectional area （＝6.34×10^{-5}m^2）
A_E : open area of check valve （＝1.54×10^{-4}m^2）
A_V : total open area of solenoid-operated valve （＝7.76×10^{-5}m^2）
c_0 : discharge coefficient of solenoid-operated valve （＝0.6）
c_f : discharge coefficient of check valve （＝0.7）
C_E : viscous damping factor of check valve （=11.8 Ns/m）
D : inner diameter of pipeline
D_E : inner diameter at check valve inlet （=16mm）
f : flow force
F_C : Coulomb friction force of check valve （＝0.15N）
g : acceleration due to gravity
h_f : head loss due to fluid friction per unit length
H : pressure head
H_V : pressure head in vessel
H_E : pressure head at downstream end of pipeline
K_E : spring constant （= 20.6 kN/m）
K_V : bulk modulus of fluid （=1.36GN/m^2）
L : length of pipeline
L_3 : length of connection area （=0.145m）
M_E : moving mass of check valve （= 49.7 g ）
P_E : pressure at downstream end of pipeline
P_S : supply pressure
P_V : pressure in vessel
q_c : volumetric fluid flow rate through check valve orifice

Copyright © 2005 by JFPS, ISBN 4-931070-06-X

q_s : volumetric fluid flow rate through solenoid-operated valve
t : time
t_w : pulse width
U_c : volume at connection part $(= 0.220 \times 10^{-4}\,\mathrm{m}^3)$
U_V : volume in vessel $(=5.0 \times 10^{-3}\,\mathrm{m}^3)$
V : average flow velocity at line section
V_E : average flow velocity at line section of downstream end
V_V : average flow velocity at line section of check valve inlet
W : ratio of current open area of solenoid-operated valve to its total open area
x : coordinate in axial direction of pipeline
Y : check valve displacement
Y_0 : check valve initial compression length $(=4.4\,\mathrm{mm})$
α : valve angle between vertical and poppet face $(= \pi/4\,\mathrm{rad})$
ν : kinematics viscosity of fluid $(=3.83 \times 10^{-5}\,\mathrm{m}^2/\mathrm{s})$
ρ : fluid density $(=853\,\mathrm{kg/m}^3)$
ζ : loss factor

INTRODUCTION

Since an oil (water) hammer generates much higher pressure than the supply pressure, it occasionally destroys a device. There are many measures that may be taken against the disadvantages of the oil hammer. However, the authors propose to actively utilize this pressure rise phenomenon. A new type of hydraulic pressure intensifier was already proposed and developed [1][2][3]. Many hydraulic machines are large and heavy. There are a large number of examples of waste from high pressure and large flow volumes supplied by a pump. Our intensifier uses an oil hammer to convert low-pressure fluid from a supply pump to a high pressure one only when necessary. Therefore, the hydraulic pressure source can be small, and energy is saved.

The purpose of this research is to apply this device to the real construction machine. A vessel is used as a model of a hydraulic cylinder without displacement. The pressure of the vessel is a control object. The volume in a vessel is made with a large capacity of 5 liters. The experiment is done to investigate the condition when a construction machine is actually working. The necessary pressure level is thought to be around 30MPa.We develop a block diagram for the simulation of the system considering the pipeline dynamics. The simulation results are easily obtained using MATLAB SIMULINK. We also obtain the accurate simulation results using Fortran program made by the authors. We research the characteristics through the experiment and simulation.

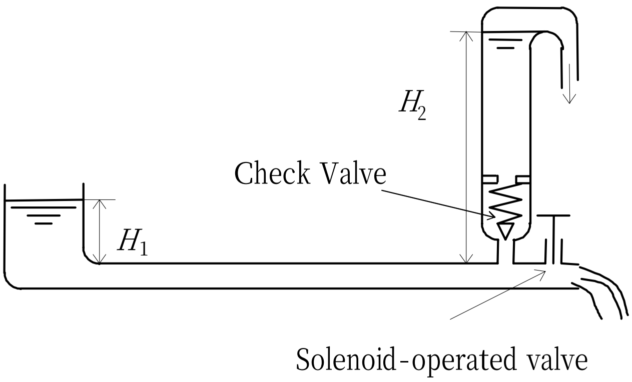


Fig.1 Concept of the new hydraulic pressure intensifier

CONSTRUCTION

Figure 1 shows the principle of the new pressure intensifier. When the solenoid-operated valve at the downstream end of the pipeline is open, fluid supplied with a constant pressure flows through the pipeline. If the valve is shut quickly, an oil hammer is generated in the pipeline. The check valve is used to release the high pressure generated. Pressure much higher than the supply pressure can be continuously released by opening and shutting the solenoid-operated valve repeatedly.

The concept is applied to the pressure intensification of a hydraulic cylinder as shown in Fig.2. This equipment is composed of a pipeline, a check valve, a solenoid-operated valve, and a personal computer for on-off operation of the solenoid-operated valve. The hydraulic cylinder is the controlled object.

When the solenoid-operated valve is kept shut, the pump pressure is directly supplied to the hydraulic cylinder. If the solenoid-operated valve is turned on, oil flows at high speed through the pipeline to the tank. By cutting off the current to the solenoid-operated valve, the valve is shut and an oil hammer is generated in the pipeline. If the pressure at position① in Fig.2 is higher than the pressure at position②, the check valve opens and high-pressure fluid is discharged into the hydraulic cylinder. The pressure in the hydraulic cylinder is made

Copyright © 2005 by JFPS, ISBN 4-931070-06-X

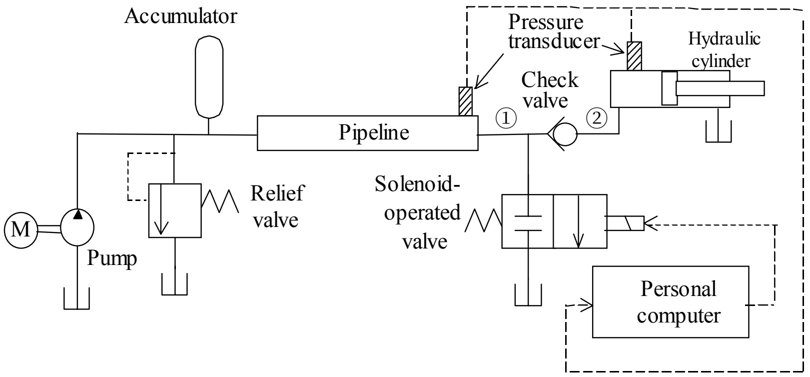


Fig2. Schematic diagram of the test ring

much higher than the one supplied by the pump. The hydraulic cylinder produces much bigger force than the force which is produced by the pressure supplied directly from the pump. When the pressure at position ① becomes lower than the pressure at position②, the check valve shuts and prevents the fluid from flowing backwards. A vessel is used as the model of a cylinder without displacement.

BASIC EQUATIONS FOR SIMULATION

Basic equations related to the pipeline, the check valve and the vessel are analyzed and shown by simulation. The interaction of an oil hammer and the check valve is considered.

Relation between pressure and flow velocity in the pipeline

In this research, the improved version [4] of Zielke's characteristics method is used to obtain the relation between the pressure and the flow velocity in the pipeline. The relations between the pressure and the flow velocities of the adjoining two points R and S, and the point N on the *x*-*t* plane [4] are given by the following equations. N is the middle and Δx away from points R and S. The time at N is Δt later than the time at R and S.

$$V_N - V_R + \frac{g}{a}(H_N - H_R) + g h_{fR} \Delta t = 0 \qquad (1)$$

$$V_N - V_S - \frac{g}{a}(H_N - H_S) + g h_{fS} \Delta t = 0 \qquad (2)$$

h_f indicates the transient pressure head loss per unit length and it is obtained using the method shown in reference [4]. When the pressure is lowed below the atmosphere pressure, vapor-liquid model is used [5][6].

Relation between pressure drop and flow velocity at the check valve

$$\pm \frac{1}{2g}\left(\frac{q_c}{c_f \pi D_E Y \sin\alpha}\right)^2 + \frac{L_3}{g}\frac{dV_V}{dt} = H_E - H_V \qquad (3)$$

(+ : regular flow — : reverse flow)

$$A_3 V_V = q_c + A_E \frac{dY}{dt} \qquad (4)$$

Motion of the poppet in the check valve

$$M_E \frac{d^2Y}{dt^2} + C_E \frac{dY}{dt} + K_E Y$$

$$= f - M_E g - K_E Y_0 - F_C \operatorname{sgn}\left(\frac{dY}{dt}\right) \qquad (5)$$

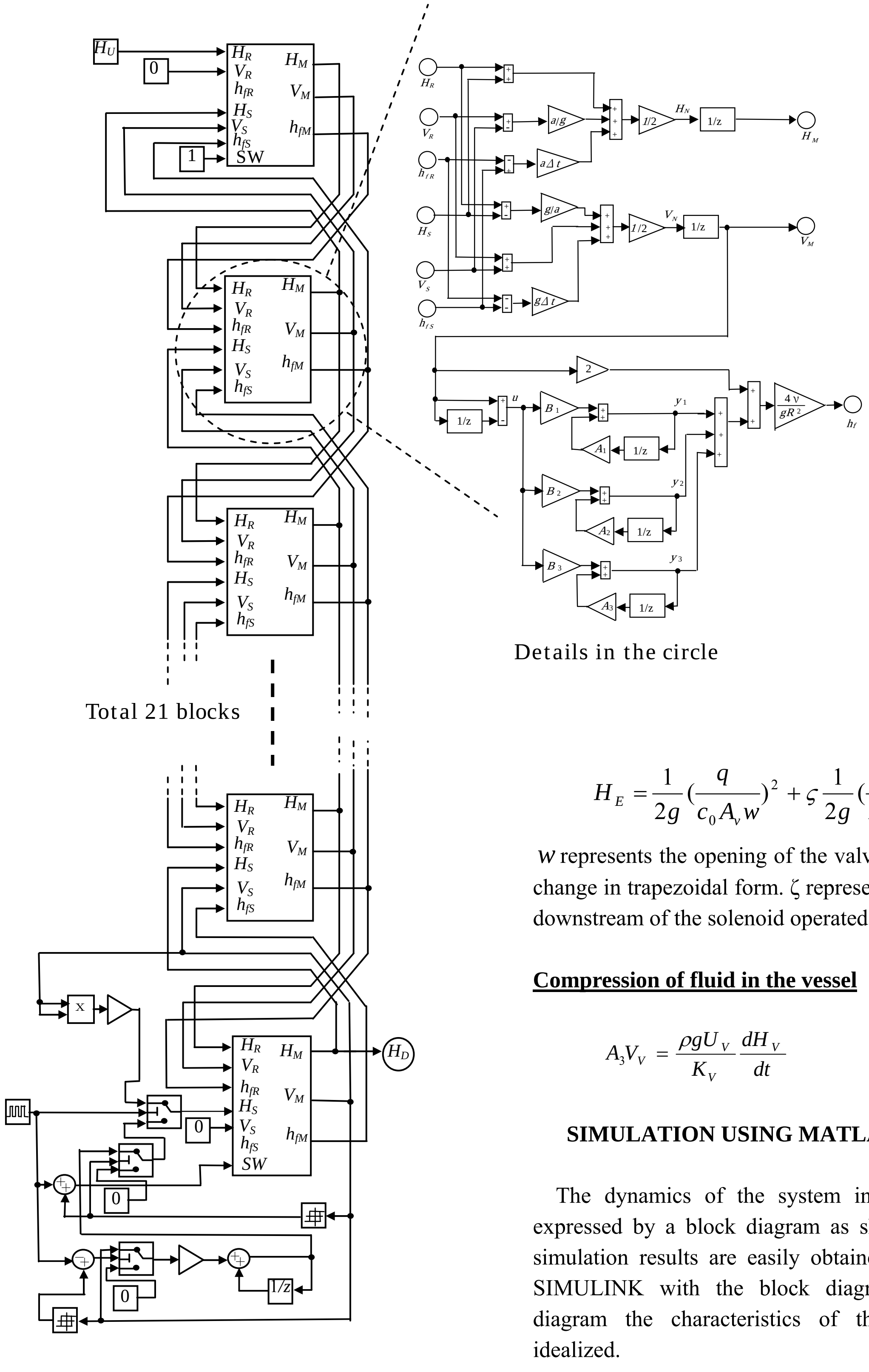
$$f = \left(1 - 4c_f \frac{Y}{D_E}\sin 2\alpha\right)\rho g A_E$$

$$\times \left(H_E - H_V - \frac{L_3}{g}\frac{dV_V}{dt}\right) \qquad (6)$$

where $Y \geq 0$ is assumed.

Equation for fluid compression at the connection between the solenoid-operated valve and the pipeline

$$A V_E - A_3 V_V - q_S = \frac{\rho g U_C}{K_V}\frac{dH_E}{dt} \qquad (7)$$



Details in the circle

Total 21 blocks

Fig.3 Block diagram of the system

$$H_E = \frac{1}{2g}\left(\frac{q}{c_0 A_v w}\right)^2 + \varsigma\frac{1}{2g}\left(\frac{q_s}{A_v}\right)^2 \qquad (8)$$

w represents the opening of the valve and is assumed to change in trapezoidal form. ζ represents loss factor at the downstream of the solenoid operated valve.

Compression of fluid in the vessel

$$A_3 V_V = \frac{\rho g U_V}{K_V}\frac{dH_V}{dt} \qquad (9)$$

SIMULATION USING MATLAB SIMULINK

The dynamics of the system including pipeline is expressed by a block diagram as shown in Fig.3. The simulation results are easily obtained using MATLAB SIMULINK with the block diagram. In this block diagram the characteristics of the check valve is idealized.

COMPARISON BETWEEN THE SIMULATION AND THE EXPERIMENT

The solenoid-operated valve is opened and closed by the frequency 8Hz and the pulse width t_w 50ms in this experiment. The frequency of 8 Hz means that the period is 125ms. The current is ON-state for 50ms during 125ms. The supply pressure P_s = 6.86 MPa. The pipeline length L = 4.15 m and the inner diameter D = 6 mm. The experimental results and the simulation results of the pressures at the downstream end and in the vessel for 0.5 second from the beginning are shown in Figs 4, 5 and 6. The results for 10 seconds are shown in Figs. 7 and 8. Fig.4 shows the simulation results of MATLAB SIMULINK. Figs.5 and 7 show the simulation results of FORTRAN program made by the authors.

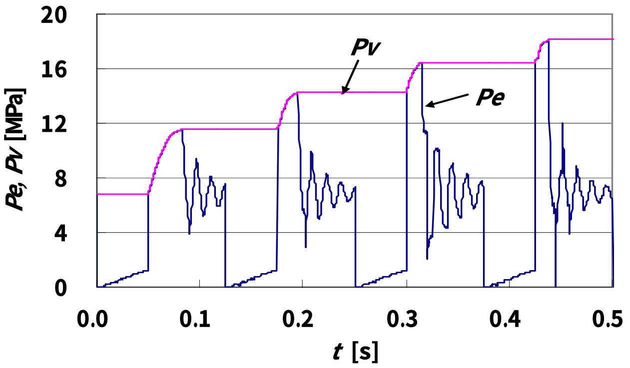


Fig.4 Pressures in the vessel (P_V) and at the downstream end (P_e) of the pipeline obtained by MATLAB SIMULINK simulation for 0.5 s from the beginning.

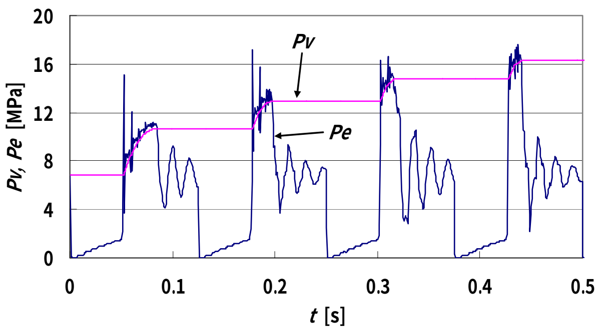


Fig.5 Pressures in the vessel (P_V) and at the downstream end (P_e) of the pipeline obtained by the simulation program made by the authors during 0.5 s from the beginning.

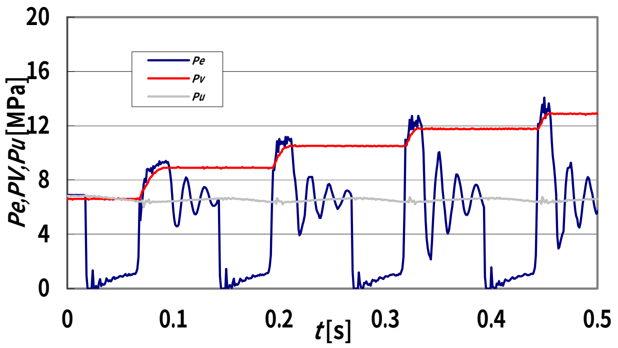


Fig.6 Experimental results of pressures in the vessel(P_V) and at the downstream end(P_e) and upstream end(P_U) of the pipeline.

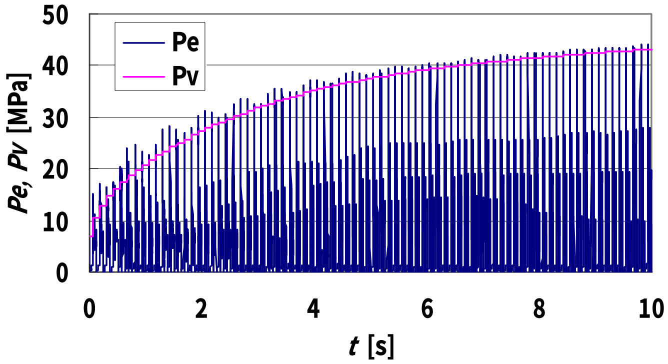


Fig.7 Simulation results of pressures in the vessel (P_V) and at the downstream end (P_e) of the pipeline obtained by the program made by the authors for 10 s from the beginning.

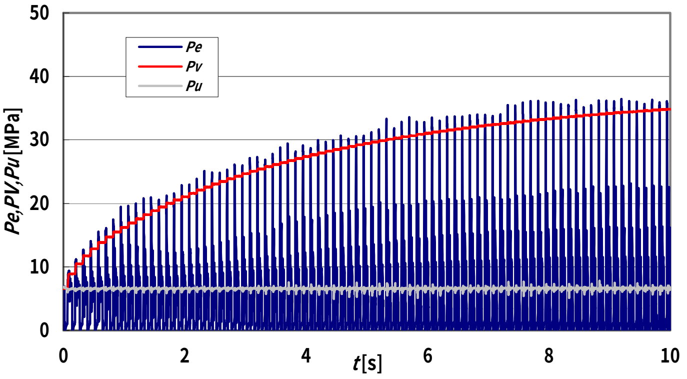


Fig.8 Experimental results of pressures in the vessel (P_V) and at the downstream end (P_e) and upstream end(P_U) of the pipeline during 10 s from the beginning.

Copyright © 2005 by JFPS, ISBN 4-931070-06-X

PRESSURE INCREMENT IN THE VESSEL

The results in Figs. 7 and 8 show that the pressure increment in the vessel almost saturates in 10 seconds and the pressure of the experiment exceeds 30 MPa.

The pressure obtained by the experiment is less than the one obtained by the simulation. The difference increases with the supply pressure increment and the inner diameter increment. The pressure at the downstream end increases when the diameter is increased to 8 mm from 6 mm. Because the pressure drop through the test pipeline is reduced due to the pressure increase at the downstream end, the flow velocity is not so increased as expected. Therefore the pressure in the vessel is not so increased as expected when the diameter is increased exceeding 6 mm.

RELATION BETWEEN THE PRESSSURE INCREMENT AND THE PIPELINE PARAMENTERS

In the previous section, the length of the pipeline is 4.15 m and the inner diameter is 6mm. The pressure obtained in the vessel, are shown in Fig.9 when the length and the diameter of the pipeline are changed.

Fig. 9 shows the pressures obtained after an oil hammer is generated 80 times. They are obtained after 10 seconds because the frequency of opening and closing the solenoid operated valve is 8 Hz.

The experimental results are smaller than the simulation results. The leakage at the poppet and the flow resistance at some places may influence the experimental results. The simulation result has a peak point to the pipeline length. The experimental result seems to have a peak point at the pipeline length longer than 4m. There is a tendency that smaller pipe diameter gets higher pressure when the pipeline length is short, and bigger pipeline diameter gets higher pressure when the pipeline length is long.

CONCLUSION

A pressure of more than 30 MPa was obtained by our intensifier from the supplied pressure 6.86 MPa. This is our target to apply this equipment to a real working machine as a construction machine.

The dynamics of the system including pipeline is expressed by a block diagram. The simulation results are easily obtained using MATLAB SIMULINK with the block diagram. Also, the simulation results are obtained by FORTRAN program made by the authors.

It is clarified that the phenomenon is expressed with a theoretical formula by comparing the experimental result and the simulation result. However, in case of a shorter pipeline, thicker diameter, or higher supply pressure, the experimental value becomes smaller than the simulation result.

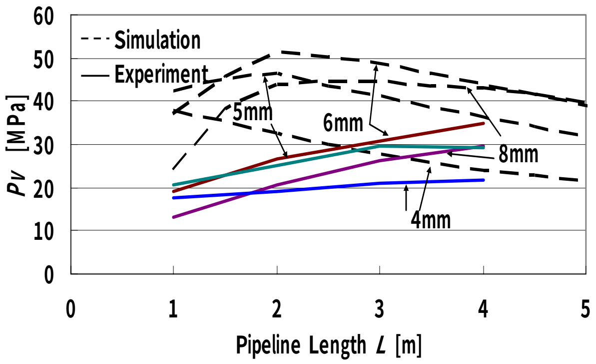


Fig. 9 Pressure in the vessel after oil hammer is generated 80 times. (Results of Simulation and experiment)

REFERENCES

[1] Suzuki, K., 1989,"Application of a New Pressure Intensifier Using Oil Hammer to Pressure Control of a Hydraulic Cylinder," ASME Journal of Dynamic Systems, Measurement and Control, 111-2, pp.322-328

[2] Suzuki, K., 1990,"A New Hydraulic Pressure Intensifier Using Oil Hammer," ASME Journal of Fluids Engineering, 112-1, pp.56-60

[3] Suzuki, K., Asahara, K., Narita, R., 2000 ,"Application of a Pressure Intensifier Using an Oil Hammer to a Hydraulic Motor Control," Trans. JSME B, 66-644, pp.1105-1111

[4] Suzuki, K., 1991,"Improving Zielke's method of Simulating Frequency-Department Friction in Laminar Liquids Flow," ASME Journal of Fluids Engineering, 113-4, pp.569-573

[5] Wylie, E. B., Streeter, V. L., 1978, "Fluid Transients," McGraw-Hill, pp136-139

[6] Sanada, K., Kitagawa, A., Takenaka, T., 1990, "A Study on Analytical Methods by Classification of Column Separations in a Water Pipeline," Trans. JSME B, 56-523, pp585-593