A Study on Control Performance of Water Hydraulic Systems (Pressure Loss and Fluid Transients in Water Pipelines)

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ABSTRACT

Compared with hydraulic oil, low viscosity of water is one of big differences in fluid property. In this paper, control performance of water hydraulic systems is investigated concentrating on pressure loss and fluid transients in pipelines. Comparisons between water and oil hydraulics are carried out through experiment and simulation. It is pointed out that water hydraulics has a merit of low pressure loss. Low dissipation and high surge pressure must be considered in designing water hydraulic systems.

KEY WORDS

Water hydraulics, Pressure loss, Fluid transients, Line, Viscosity, Pressure surge

NOMENCLATURE

A :	cross sectional area	V :	velocity
c :	wave velocity	λ :	frictional coefficient
d :	diameter	ν :	kinematic viscosity
g :	gravitational acceleration	ρ :	density
H :	pressure head		Subscript
h_f :	pressure head loss per unit length	w :	water
K :	bulk modulus	o :	hydraulic oil
L :	length		
Δp :	pressure loss or pressure rise		
Q :	flow rate		
Re :	Reynolds number		

INTRODUCTION

It has been said that viscosity of water is lower than that of hydraulic oil and that it must lead to some merit. However the discussions were rather qualitative. For

further development of water hydraulics, quantitative discussions have been expected to illustrate the merit of water hydraulics and to point out the technical matters to be solved. In this paper, from the aspect of pressure loss and fluid transients in pipelines, control performance of water hydraulic systems are discussed quantitatively.

PRESSURE LOSS

Pressure losses of water and hydraulic oil with a pipe having the same dimensions are compared. Pressure loss through a pipe Δp is:

$$\Delta p = \frac{\lambda \rho L}{2d} V^2 \quad (1)$$

Assuming laminar flow for hydraulic oil and turbulent for water, the frictional coefficient λ is written as :

$$\left[\begin{array}{l} \text{[Water flow]} \\ \lambda_w = \frac{0.3164}{\sqrt[4]{Re_w}}, \quad (2) \end{array} \right. \quad \left[\begin{array}{l} \text{[Oil flow]} \\ \lambda_o = \frac{64}{Re_o}, \quad (3) \end{array} \right.$$

$$\left. \begin{array}{l} Re_w = \frac{Vd}{\nu_w}, \quad (4) \end{array} \right\} \quad \left. \begin{array}{l} Re_o = \frac{Vd}{\nu_o}, \quad (5) \end{array} \right.$$

where Re_w and Re_o are Reynolds number for water and oil flow, respectively.

Dividing flow rate Q by cross sectional area, the velocity V is obtained:

$$V = \frac{4Q}{\pi d^2}. \quad (6)$$

Arranging the above equations, the ratio of pressure loss of water Δp_w to that of hydraulic oil Δp_o is:

$$\frac{\Delta p_w}{\Delta p_o} = \frac{\lambda_w \rho_w}{\lambda_o \rho_o} = \frac{0.3164}{\sqrt[4]{Re_w}} \frac{Re_o}{64} \frac{\rho_w}{\rho_o} = 6.46 \left(\frac{Q}{d} \right)^{3/4}. \quad (7)$$

When both flows are turbulent, the ratio becomes:

$$\frac{\Delta p_w}{\Delta p_o} = \frac{\lambda_w \rho_w}{\lambda_o \rho_o} = \frac{0.3164}{\sqrt[4]{Re_w}} \frac{\sqrt[4]{Re_o}}{0.3164} \frac{\rho_w}{\rho_o} = 0.474. \quad (8)$$

The ratios were calculated using properties in Table 1 and plotted in Fig.1 as a function of flow rate Q for

various diameter d . The ratios are less than unity. This means pressure loss of water is lower than that of hydraulic oil. The result points out that a water line has merit of low pressure loss as power transmission line.

Table 1 Typical fluid properties

	Water	Hydraulic Oil
ρ (kg/m ³)	1000	880
ν (m ² /s)	1.0×10^{-6}	34.0×10^{-6}
K (GPa)	2.4 (at 10MPa)	1.5

Fig.1 Pressure loss of a water line compared with a hydraulic oil line

FLUID TRANSIENTS IN A SIMPLE LINE

Pressure surge may be caused by instantaneous operation of a valve and by sudden stoppage of an actuator. Pressure rise and its attenuation are of interest from a technical point of view.

Wave velocity c is:

$$c = \sqrt{\frac{K}{\rho}}. \quad (9)$$

Assuming the fluid parameters in Table 1:

$$\left[\begin{array}{l} \text{[Water]} \\ c = 1550 \text{ m/s}, \end{array} \right. \quad \left[\begin{array}{l} \text{[Oil]} \\ c = 1305 \text{ m/s}. \end{array} \right.$$

Pressure rise due to pressure surge is:

$$\Delta p = \rho c \Delta V. \quad (10)$$

Again using the fluid properties:

$$\begin{array}{|l} \text{[Water]} \\ \Delta p_w = 1.55 \Delta V \text{ (MPa)} \end{array} \quad \begin{array}{|l} \text{[Oil]} \\ \Delta p_o = 1.15 \Delta V \text{ (MPa)} \end{array}$$

Pressure rise of water is about 30% higher than that of hydraulic oil.

Fig.2 Pressure surge due to sudden stoppage of a piston

Numerical simulation was carried out in a model as shown in Fig.2. Traveling piston suddenly stops at the stroke end resulting in pressure surge in the line. Equation of motion and continuity equation in the fluid line is [1]:

$$\frac{\partial V}{\partial t} + g \frac{\partial H}{\partial x} + gh_f = 0 \quad (11)$$

$$\frac{\partial H}{\partial t} + \frac{c^2}{g} \frac{\partial V}{\partial x} = 0 \quad (12)$$

The method of characteristics was applied to the simulation. Initial flow is turbulent for water and laminar for hydraulic oil. As a friction term h_f turbulent flow was assumed for water and unsteady laminar friction [2] was used for hydraulic oil:

[Water]

$$h_f = \frac{\lambda}{2dg} V |V|, \quad (13)$$

[Oil]

$$h_f = \frac{8\nu}{gR^2} V + \frac{4\nu}{gR^2} \int_0^t \frac{\partial V}{\partial t}(u) W(t-u) du, \quad (14)$$

where R is radius of pipe and W is a weighting function.

Simulation results of transient pressure in the cylinder p_H are shown in Fig.3. Supply pressure p_s is also plotted as a broken line. The pressure rise of water is higher than that of hydraulic oil. The attenuation of pressure oscillation is a big difference. In water, due to low viscosity, surge pressure may remain for a longer period than that of hydraulic oil.

The minus pressure may cause cavitation phenomena. The cushioning of piston or shock-less operation of control valve might prevent it. As a modern manner, control system using a commercial servo valve offers the user more intelligent and flexible function.

(a) Water

(b) Hydraulic oil

Fig.3 Simulation results of transient pressure in the cylinder

EXPERIMENTAL STUDY

The fluid transients in water lines were investigated through experiment using a single closed-end pipe as

shown in Fig.4. The line was a pipe of SUS304 having a diameter of 10 mm and a length of 36 m. With a quick switching valve, the inlet pressure was increased to 0.2 MPa from 0 MPa. Temperature of water was 16°C. Corresponding kinematic viscosity is $1.05 \times 10^{-6} \text{ m}^2/\text{s}$ and the density is 999 kg/m^3 . Transient pressures at the upstream, midpoint and downstream were measured with semi-conductive pressure sensors.

Fig.4 Closed-end pipe

Fig.5 Experimental results of transient pressures

An example of experimental results is shown in Fig.5. From the records of wave traveling along the pipe, the wave velocity c was about 1310 m/s. Wave velocity can be calculated considering elasticity of pipe wall [3]:

$$c = \frac{\sqrt{K/\rho}}{\sqrt{1 + [(K/E)(d/e)]c_1}} = \frac{1414}{1.045} = 1353 \text{ (m/s)}. \quad (15)$$

Due to elasticity of pipe wall, the wave velocity of 1353

Fig.6 Comparisons of transient pressures at the blocked end of water and hydraulic oil

m/s becomes smaller than that of the equation (9) ($c=1414 \text{ m/s}$). In the calculation, bulk modulus of water $K=2.0 \text{ GPa}$ (at atmosphere), Yong modulus of pipe wall $E=200 \text{ GPa}$, wall thickness $e=1\text{mm}$ were used.

The coefficient c_1 depends on the way of the support of pipes. In experiment, the pipe was fixed in a heavy steel block and therefore $c_1 = 1 - \mu^2$, where μ is Poisson ratio of 0.3. The calculated wave velocity shows a good agreement with the experimental one.

In the case of hydraulic oil, typical bulk modulus is 1.5 GPa and the density is 850 kg/m^3 . With the same pipe as that of the experiment for water, wave velocity of hydraulic oil is calculated as 1328 m/s from the equation (9), and from the equation (15) as 1284 m/s . It is still smaller than that of water line (1353 m/s).

Simulation results of transient pressure at the closed-end are shown in Fig.6. Measured and simulated results for water p_w are plotted in the top and middle figures, respectively. The simulated results have a good agreement with the measured results. In the bottom figure, simulated results for hydraulic oil p_o is plotted.

A wave velocity of 1284 m/s as discussed in the above and a kinematic viscosity of $34.0 \times 10^{-6} \text{ m}^2/\text{s}$ were used. The wave attenuation is much different between water and hydraulic oil.

Due to the limit of valve operating speed, the upstream pressure p_U was not a sharp step. Therefore pressure waves at the other points were rounded. In the simulation, the upstream pressure p_U was assumed to be a step and therefore the sharp edge of the wave form was simulated clearly. If the upstream pressure accurately considered in the simulation, better agreement will be expected.

A CASE STUDY

With an injection cylinder circuit taken as an example, comparisons have been carried out. The circuit is shown in Fig.7. The injection cylinder was driven by an accumulator through a cartridge valve, pipes I and II. The circuit was simplified, but the same dimensions as a commercial injection machine were used. Fluid properties are listed in Table 2.

Table 2 Fluid properties of an injection cylinder

	Water	Hydraulic oil
ρ (kg/m ³)	992.2 (at 40°C)	863.0 (at 40°C)
ν (m ² /s)	0.658×10^{-6} (at 40°C)	32.4×10^{-6} (at 40°C)
K (GPa)	2.4 (at 10MPa)	1.5 (Typical)

In the accumulator, adiabatic change of gas was assumed. The catalogue data of pressure-drop of the cartridge valve was used. The injection cylinder was traveling at a speed of 3.7 m/s initially and suddenly stopped at its stroke end. Fluid compressibility in the cylinder volume was considered. Initial flow rate was 0.0115 m³/s (692 L/min), that means a velocity of 9.96 m/s. Initial Reynolds number was about 580,000 for water and about 11,800 for hydraulic oil. Initial flow was turbulent for both cases. Therefore turbulent friction of the equation (13) was used.

Wave velocities from the equation (9) are:

$$\begin{array}{l|l} \text{[Water]} & \text{[Oil]} \\ c=1560 \text{ m/s} & c=1320 \text{ m/s} \end{array}$$

Pressure rises due to sudden stoppage of the piston are

Fig.7 Simplified circuit of an injection cylinder

Table 3 Initial flow conditions

d (mm)	A (m ²)	Q (m ³ /s)	V (m/s)	Water			Hydraulic oil		
				Re	Flow	λ	Re	Flow	λ
38.4	1.16×10^{-3}	0.0115	9.96	580,000	Turbulent	0.012	11,800	Turbulent	0.030

estimated from the equation (10):

[Water]	[Oil]
$\Delta p = 15.4 \text{ MPa}$	$\Delta p = 11.3 \text{ MPa}$

The initial operating pressure was 6MPa. Pressure rises up to 17.3 MPa for hydraulic oil and 21.4 MPa for water. An example of simulation results is shown in Fig.8. Pressure surge may occur even in hydraulic oil. Pressure rise of water is higher than that of hydraulic oil as estimated in the above. Fluid volume in the cylinder is relatively small in this circuit, the effect of fluid compressibility in the volume is not dominant. Wave propagation along the pipes plays an important role in the fluid transients. Because of turbulent flow, attenuation of wave depends on the frictional coefficient. It is 0.030 for hydraulic oil and 0.012 for water. Friction loss of water is less than half of hydraulic oil.

(a) Water

(b) Hydraulic oil

Fig.8 Simulation results of transient pressure in the injection cylinder

It is the same as Fig.3 that modern control techniques could reduce the cavitation caused by the negative pressure.

CONCLUSIONS

Because of low viscosity of water, a water pipeline has merit as power transmission line. This means that water hydraulic systems show superior control performance in the application having a long pipeline or a pipeline of small diameter. However, due to instantaneous operation of control valves and sudden stoppage of actuators may cause pressure surge. The pressure in a pipe may oscillate for a relatively long period. Therefore some techniques must be applied to avoid and reduce the pressure surge. Control system using a servo valve will offer the user intelligent and flexible function.

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