A PRESSURE CONTROL BY A NEW INTENSIFIER USING OIL HAMMER

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ABSTRACT

A new type of hydraulic pressure intensifier was previously proposed by the author, which operates on the principle that an oil hammer is generated continuously in the pipeline by the on-off operation of a solenoid operated valve, located at the downstream end of the pipeline, and only the high pressure fluid is discharged through a check valve. In addition, a method to utilize the intensifier for pressure control of a hydraulic cylinder by adjusting a pulse to the solenoid operated valve was already proposed.

In this paper, a pressure control system utilizing this intensifier is developed to generate a wave form according to a desired input. The empirical formula which relates the pulse width to the corresponding pressure increase is established in advance and memorized in a computer. When the desired pressure is given to the computer, it calculates the pulse width automatically through the empirical formula and sends a pulse to a solenoid operated valve. Since this system is digitally controlled using a micro computer, it has an advantage of having an option for a learning function.

KEYWORDS: Hydraulics, Intensifier, Oil Hammer, Pressure Control, Solenoid Operated Valve

NOMENCLATURE

D = inner diameter of line
K = bulk modulus of fluid
L = length of line
 P_h = pressure after increase
 P_o = output pressure
 P_s = supply pressure

P_u = pressure before increase
p = pressure
Q = time average volumetric fluid flow rate
t = time
 t_w = pulse width
V = volume of pressure vessel
y = valve (spool) displacement
 η = efficiency
 ν = kinematic viscosity of fluid
 ρ = fluid density

subscripts

1, 2, 3: flow positions (Fig.2, 3 & 6)

1. INTRODUCTION

Since an oil (water) hammer generates greater pressure than that supplied to a pipeline and sometimes causes equipment breakdown, many attempts have been made to reduce the pressure. The author proposes to actively utilize this pressure rise. A new design of a new type of hydraulic pressure intensifier was previously proposed and tested. This intensifier operates on the principle that an oil hammer is generated in a pipeline and only the high pressure fluid gets discharged through a check valve [1,2]. In addition, a method to apply this equipment to a pressure intensification of a hydraulic cylinder [3] and its pressure control [4] was proposed in previous papers.

The concept of the intensifier is shown in Fig.1. Low pressure fluid is supplied to the upstream side of a pipeline and the fluid path is opened and closed by a solenoid operated valve located at the downstream end of the pipeline.

While the solenoid operated valve is open, the fluid flows at high speed through the pipeline to an exit. Immediately after the valve is

closed, high pressure is generated by an oil hammer and high pressure fluid is discharged through a check valve. Consequently, a pressure much higher than the supply pressure is obtained. This principle is similar to a hydraulic ram [5], a unique pump which was invented two hundred years ago. The valve, equipped at the downstream of the hydraulic ram, continues the open-close operation automatically by the fluid force without any other external input. It is used mainly to deliver water to higher elevation.

Since the new intensifier of this research is intended for the oil hydraulic equipment, the discharge pressure levels required are about 10-30 times greater than those encountered by a hydraulic ram, and a function to control the generated pressure by adjusting the on-off operation of the solenoid operated valve is added.

When the solenoid operated valve at the downstream end is opened, the fluid in the pipeline is accelerated. An oil hammer is generated by the rapid closure of the valve, and high pressure fluid is discharged through a check valve, compressing the fluid in the chamber of the cylinder. Therefore, the inside pressure is increased stepwise by every on-off operation. The value of the pressure increase is determined by the total number of discharges and its strength.

Since the fluid velocity which is present just before the solenoid operated valve is closed, influences the strength of an oil hammer, the fluid velocity is controlled by an open time period of the solenoid operated valve. Because fluid velocity is accelerated rapidly from zero after the opening of the solenoid operated valve, the open time period is controlled by the width of the pulse to the solenoid operated valve and the value of pressure increase by an oil hammer is controlled.

A micro computer generates the signal for switching in order to operate the solenoid operated valve according to desired patterns.

For conventional pressure control, the pressure drop through a metering orifice is varied by adjusting the area in order to control the output pressure. Since the pressure drop acts by dissipating energy, the efficiency is extremely low especially when the output pressure is much lower than the supply pressure. Since the new method of this research controls an output pressure by a new principle that utilizes fluid inertia, high efficiency is expected.

In this research, a new type of pressure control is realized to generate a desired wave form. In addition, it can correct an output

pressure by observing a wave form one cycle before.

2. CONSTRUCTION OF A NEW SYSTEM

The concept shown in Fig.1 is applied to the pressure intensification of a hydraulic cylinder as shown in Fig.2. This intensifier is composed of a pipeline, a check valve, a solenoid operated valve, and a micro computer to switch the current. The pulsation of the fluid with constant average pressure, supplied by a low pressure pump, is removed by an accumulator. The fluid is then sent to the upstream side of the pipeline. When the current is supplied to the solenoid operated valve, it is in the open state. The fluid path is now free and the fluid flows at high speed through the pipeline and solenoid valve to the tank. When the current is turned off, the valve is shut and an oil hammer is generated. As long as the pressure at point 2 is higher than that at point 3, the check valve is open and high pressure fluid is discharged through it. When the pressure at point 2 becomes lower than that at point 3, the check valve is closed preventing a reverse flow. The discharged fluid compresses the fluid in the chamber of a hydraulic cylinder and raises the pressure by a definite value.

Fig.1 Concept of a hydraulic pressure intensifier

Fig.2 Application of an intensifier to a hydraulic cylinder

An LSI (CTC = Counter Timer Circuit) which reads a system clock, is built in the micro computer and set up to detect the time at intervals of 50 μ s in order to switch the direct current of the solenoid operated valve at the desired time intervals.

When the solenoid operated valve is kept closed, the pressure at the pump is supplied directly to the hydraulic cylinder, which is operated as usual with the pump pressure by the manually operated valve. If the solenoid operated valve continues the open-close operation at the condition shown in the Fig.2, the pressure is intensified and the hydraulic cylinder produces a force several times higher than it does in a usual application.

In this research, the pressure control is investigated by using the equipment shown in Fig.3. The pressure vessel is used as an idealized model of a hydraulic cylinder and simulates one of two chambers of the cylinder which is assumed not to displace. Therefore, the pressure intensification is simulated at the final stage of the press process of an oil hydraulic press or at cramping of a cramping equipment. The solenoid operated valve (II) is used to reduce the pressure in the pressure vessel. The throttle valve moderates the shock when pressure is reduced.

3. EMPIRICAL FORMULA TO SHOW THE VALUE OF PRESSURE INCREASE

If the desired pressure is entered interactively by the user at the keyboard, the micro computer calculates the suitable pulse width, generates the pulse with the width, and controls the output pressure.

On the other hand, the relationship between pulse width and pressure increase can be obtained theoretically by numerical calculation and has been confirmed to predict the tendency of the experimental results [4]. It was clarified that parameters which affect the pressure increase are pipeline length, diameter, volume of a pressure vessel, fluid viscosity, supply pressure, the pressure before an oil hammer, and pulse width. However, it is not sufficient to utilize this calculation for the purpose of this pressure control because it takes much time to obtain even one result and the accuracy is not enough. Therefore, the equation which shows the relationship among the pulse width, the pressure increase, and the pressure before an oil hammer, is obtained by experiments in advance.

The experimental result for the pressure increase is shown in Fig.4 when the other system parameters are constant. The pulse width t_w is shown by third order in Eq.(1):

$$t_w = a_0 \left(\frac{P_h - P_u}{P_s} \right)^3 + a_1 \left(\frac{P_h - P_u}{P_s} \right)^2 + a_2 \left(\frac{P_h - P_u}{P_s} \right) + a_3 \quad (1)$$

where P_u and P_h are pressures before and after an oil hammer respectively. a_i is also shown by third order of P_u in Eq.(2).

$$a_i = b_{i0} \left(\frac{P_u}{P_s} \right)^3 + b_{i1} \left(\frac{P_u}{P_s} \right)^2 + b_{i2} \left(\frac{P_u}{P_s} \right) + b_{i3} \quad (i=0,1,2,3) \quad (2)$$

b_{ij} ($i, j = 0, 1, 2, 3$) are determined by least squares as the following. First, the coefficients of equation (1), a_i ($i = 0, 1, 2, 3$) are determined by using least squares to the experimental data between t_w and P_h for each constant P_u . Next, the coefficients of equation (2), b_{ij} ($i, j = 0, 1, 2, 3$) are determined also by using least squares to the relations already obtained between a_i and P_u . Their values are listed in Table 2. As t_w in equation (1) can be obtained using a_i which are obtained using sixteen experimental constants in Eq.(2), b_{ij} , micro computer calculates the pulse width by these equations. The solid lines in Fig.4 show the results calculated in this way.

Fig.3 Schematic diagram of the test rig

Fig.4 Pulse width t_w and pressure P_h

Table 1 Parameters

Parameter	Value
D	5 mm
K	1.36 GN/m ²
L	4.15 m
P _s	1.96 MPa
v	0.383 x 10 ⁻⁴ m ² /s
ρ	853 kg/m ³

Table 2 b_{ij}

i \ j	0	1	2	3
0	0.0721	-0.478	1.05	-0.614
1	-0.189	1.12	-2.39	1.33
2	1.02	-0.637	1.23	-0.642
3	-0.0129	0.0787	-0.141	0.0788

4. CORRECTION OF OUTPUT PRESSURE

If the system parameters deviate, an error generates between the real output pressure and the desired value. The main parameter deviation is viscosity change caused by the temperature change of fluid in the pipeline. Even if the temperature of oil in a tank is kept constant, it is difficult to keep the fluid temperature constant in the pipeline because of heat radiation to the atmosphere around the pipeline. If the fluid viscosity changes, the pressure increase is affected strongly because the fluid velocity changes and consequently the strength of an oil hammer changes. Therefore, feedback control is utilized in order to reduce the error by using a merit of a micro computer as shown in Fig.5.

The micro computer is able to observe the pressure in the vessel as well as calculate the pulse width and generate the pulse. When the pressure is intentionally increased and decreased repeatedly, an error between the increased pressure and the desired value is measured every time and the next pulse is generated after calculating the pulse width to reduce the error according to a computer program.

Fig.5 Block diagram of the pressure control system

(1) Conventional pressure control

(2) New pressure control

Fig.6 Comparison of two methods for pressure control

5. EFFICIENCY OF THE PRESSURE CONTROL

The efficiency of the new method of this research is compared with the conventional method when the supply pressure is constant. Each concept is shown in Fig.6. The efficiency of the new method is measured when an oil hammer is generated continuously, keeping the output pressure at the exit of the check valve in Fig.6(2), P_o, various constant values. The details are reported in literature [2].

The efficiency η is defined by equation (3).

$$\eta = \frac{P_o Q_3}{P_s Q_1} \quad (3)$$

where P_s is the constant supply pressure. As the volumetric fluid flow rate at point 1 and 3 are both intermittent, Q₁ and Q₃ are their time averages respectively. Experimental and calculated results are shown in Fig.7 concerning pulse width t_w, output pressure P_o and efficiency η [2]. The maximum values of the experimental efficiencies of Fig.7 concerning the pulse width t_w at various constant output pressure P_o's are plotted in Fig.8.

On the other hand, the efficiency of the conventional method shown in Fig.6(1) is calculated by the

following equation because $Q_1 = Q_3$ in equation (3).

$$\eta = \frac{P_0}{P_s} \quad (4)$$

The relationship between the output pressure P_0 and the efficiency η is shown by solid line in Fig.8 when the supply pressure P_s of the conventional method is assumed to be the maximum output pressure of the intensifier, (12.3 MPa). The efficiency of the conventional method is proportional to the output pressure. It becomes 100 % if the output pressure is equal to the supply pressure, which is the maximum output pressure available by this method.

The ratio of the energy loss in this case is

$$1 - \eta = \frac{P_s - P_0}{P_s} \quad (5)$$

This is the ratio of the pressure drop at the metering orifice to the supply pressure.

Meanwhile, the new method has an opposite tendency. The efficiency is high for low output pressure and there exists the range where it exceeds conventional one. The efficiency becomes lower as the output pressure becomes higher.

For the conventional method, the discharge pressure level of the supply pump should be or exceed the maximum value of the necessary output pressure. The new method has a big advantage because its supply pressure level may be about a sixth of the maximum value of the necessary output pressure.

Fig.7 Efficiency η versus pulse width t_w for various output pressure P_0

6. EXPERIMENTAL RESULTS

Fig.9 shows pulse output signal of the micro computer, e_c , displacement of the solenoid operated valve, y , pressure at the downstream side of the pipeline, p_2 , and the pressure in the pressure vessel, p_3 . The pressure p_3 is increased four times by the value of 1 MPa for every cycle.

Four pulses with different widths are sent to the solenoid operated valve (I) of Fig.3 in this case and four oil hammers are generated. After that, the solenoid operated valve (II) is opened and the pressure p_3 is reduced for the

Fig.8 Efficiency of two methods for pressure control

Fig.9 Responses of the system to pulse signal

next cycle as shown in Fig.9 when $t < 0$.

If the value of pressure increase for every oil hammer and the value at the beginning is input to the micro computer, it calculates the pressure p_3 before and after every oil hammer, calculates the pulse widths, and outputs pulses to the solenoid operated valve.

When the solenoid operated valve (I) is in the closed position, the fluid in the pipeline is at rest. When the valve is opened by a pulse signal, the pressure at the downstream end of the pipeline, p_2 becomes nearly zero and the fluid in the pipeline is accelerated. The pressure p_2 increases suddenly by the rapid closure of the valve (I) after the acceleration dependent on the pulse width. Since fluid is discharged through the check valve into the pressure vessel and compresses it, the inside pressure p_3 is increased according to the pulse width. Because the check valve closes with the pressure decrease in the pipeline, the pressure in the vessel is kept at the increased value. The pressure in the pipeline, p_2 undergoes a damped oscillatory behavior which eventually converges to the value of the supply pressure.

Fig.10 shows the experimental result when rectangular wave forms are generated by the repetitions both of a pressure increase due to an oil hammer and a decrease due to opening of the solenoid operated valve (II). It is shown that the increased pressure is gradually approaching to a desired value (3.4 MPa) by the correction of this system.

Fig.11 shows the rectangular wave form produced in a same way with period 1.37 s and 0.69 s.

Fig.12 shows the results for various pressure amplitudes. Stability is not good for small pressure amplitude. This is attributed to the reason that the value of pressure increase deviates much with the small change of the pulse width as predicted from Fig.4 when the desired output pressure is low.

Fig.10 Correction process of output pressure

Fig.11 Rectangular wave forms of pressure p_3 with different periods

Fig.12 Rectangular wave forms of pressure p_3 with various amplitudes

Fig.13 Wave forms similar to saw tooth wave

Fig.13 shows the results when the tests shown in Fig.9 are repeated with different periods. The wave forms become similar to saw tooth wave forms if the each pressure increase for one pulse is made small and the number of pulses during one cycle is increased.

7. CONCLUSION

Pressure is controlled by a new intensifier using oil hammer which was invented by the author. This method is based on an extremely different principle than that of a usual one.

Many advantages of the new method are clarified as follows.

- (1) A pressure higher than the supply pressure is generated.
- (2) Continuous value of pressure is obtained by switching only two solenoid operated valves without a DA converter or an analog circuit. Therefore, the electrical circuit is simple and has an advantage, particularly for a micro computer control.
- (3) As the regularity of an oil hammer is utilized for pressure control, it has good repeatability and robustness against contamination in the fluid.
- (4) As the inertia of the fluid is utilized for pressure control instead of usual pressure losses, it has a

possibility of pressure control with higher efficiency than the usual method.

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