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Hydraulic Drive Dynamics Upon Pressure Line Failure

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Abstract. The present paper addresses the process of loss of piping integrity of a hydraulic drive upon sudden failure of pressure line. We provide a theoretical analysis of pressure dynamics in pressure and drain lines with a view to find information parameters for development of devices precluding significant losses of hydraulic fluid. Tests of a prototype device showed a high degree of hydraulic drive protection.

1. Introduction

Practical application of hydraulic drive in mobile building machines has shown high efficiency thereof in comparison to other types of drives. Capacities of hydraulic drives are increased continuously, reaching the capacity of main engine. Hydraulic fluid consumption amounts to 5-15 liter/s, and hydraulic fluid pressures – to 28-40 MPa [5, 6, 7, 8, 10, 11, 12].

Loss of hydraulic system integrity upon sudden failure of pressure lines, typically of high-pressure hoses (HPH), results in significant losses of hydraulic fluid. According to operation organizations of the Russian Far East, hydraulic fluid losses in case of a single HPH rupture, depending on machine type and hydraulic drive capacity, vary from 50 to 100 liters.

Hydraulic oil spillage contaminates soil on construction and logging sites, comes in contact with ground waters and, generally, adversely affects an environmental situation.

Therefore, the problem of development of eco-friendly environmentally safe hydraulic drives is gaining ever-greater importance.

High-pressure hose failure takes place almost in no time due to the poor quality of swaging of metal stop valving and, therefore, it is important to estimate losses of hydraulic fluid [17].

Hydraulic oil is a petroleum derivative. Pursuant to Order No. 786 On Approval of Federal Classificatory Catalogue of Wastes issued December 02, 2002 (last updated on July 30, 2003), hydraulic oils are referred to as hazard class 3 waste, i.e. moderately hazardous waste. Though the degree of adverse effect of hazard class 3 waste on the environment is regarded as moderate, the effect still results in the dysfunction of ecosystem. The period of ecosystem restoration after the hazard reduction makes no less than ten years. Hydraulic oil spillage is an obvious breach of environmental and public health requirements [14, 15, 16, 17, 18, 22].

In its turn, replacement of hydraulic fluid in case of failure accident is quite expensive as such—this is an economic aspect of the problem. Two hundred liters of imported hydraulic oil cost as much as fifty thousand rubles in the average.

Thus, hydraulic system protection from accidental fluid release is an economic and, to a considerable extent, ecological concern.

2. Materials and Methods

The purpose of this paper consists in the research into the processes of loss of piping integrity in hydraulic systems of mobile machines and development of devices to protect them from hydraulic fluid losses. Dynamic analysis of hydraulic drive behavior will enable one to obtain information parameters and identify the structure of hydraulics protection system.

Line failure takes place due to pressure spikes upon a delay in relief valve action, especially in winter time, as well as poor swaging of stop valving.

One of the first papers on development of protection devices to preclude accidental fluid release from hydraulic systems was published by Y.N. Smirnov of Leningrad Mechanical Institute. [24]. In [2, 3, 27], results of engineering developments aimed at accidental hydraulic fluid release control are presented. At the Pacific National University, an emergency valve was developed and successfully applied to excavator ЭО-4121 [1]. Upon HPH failure, hydraulic fluid from the pump is delivered to a tank via the emergency device, thus bypassing the destroyed section of the hydraulic system. The number of hydraulic fluid leakage on the ground is reduced by a factor of several ten times.

Hydraulic drive design diagram is shown in Figure 1.

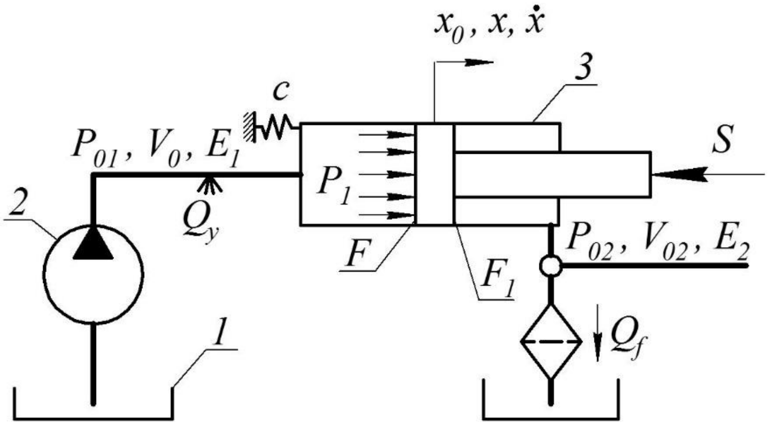

Figure 1. Hydraulic drive design diagram.

Hydraulic fluid from tank 1 is delivered by pump 2 to hydraulic cylinder 3 with force S being applied to the cylinder rod. Implement hydraulic cylinder 3 is mounted on the base section of the machine characterized by elasticity c. When pressure reaches a value of P_o corresponding to the line rupture pressure, hydraulic leaks to the ground take place, the hydraulic cylinder rod is displaced by the action of elastic component to cause extra leakage in addition to leakage from pump 2. Line pressure is decreased and a volume of fluid produced by compressibility thereof is released.

Let's write the equation of fluid flow from the damaged line section as [5, 6, 7, 8, 9, 10, 11, 12]:

$$Q_H^T - \sigma \cdot \mathrm{P} + \frac{V_0}{E} \cdot \frac{dP}{dt} + X \cdot F = Q_y, \quad (1)$$

where Q_H^T is pump theoretical delivery, cm^3/s;

σ is the pump leakage flow factor, cm^5/kg·s;

V_0 is a volume of hydraulic fluid in pressure line, cm^3;

E is the reduced modulus of elasticity of hydraulic fluid and hydraulic system, kg/cm^2;

P is pressure, kg/cm^2;

F is the rod area, cm^2;

Q_y is a leakage flow rate, cm^3/s.

Let's express leakage factor as:

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$$\sigma = \frac{(1-\eta)\cdot Q_H^T}{P_H},$$

where η is the hydraulic pump volume efficiency, $\eta = 0{,}94\ldots0{,}96$;

P_H is normal pressure, kg/cm^2.

Let’s write leakage flow rate Q_y in linearized form as:

$$Q_y = \frac{\delta Q}{\delta P}\cdot P_1, \text{ or } Q_y = A\cdot P_1, \text{ cm}^3$$

where A is a leakage factor, cm^5/kg·s.

As a result of line failure, pressure is decreased sharply and then remains constant to be determined by the cross-sectional area of the damaged portion of the line, P_{const}.

Let’s define hydraulic fluid leakage flow during this period as:

$$Q_y = A\cdot P_{const}.$$

It can be assumed that the leakage flow is equal to the pumping capacity, then:

$$A = \frac{Q_H^T - \sigma\cdot P_{const}}{P_{const}} = \frac{Q_H^T}{P_{const}}\left[1-\frac{P_{const}}{P_н}\cdot(1-\eta)\right] \text{ or } A = \frac{Q_H^T - \sigma}{P_{const}}$$

Let’s obtain rod displacement X under the action of elastic forces from:

$$X = \frac{(P_0 - P_1)\cdot F}{C}.$$

Let’s find the rod displacement rate based on the assumption that inertial forces can be neglected.

With due regard to the terms and assumptions accepted, (1) takes on form:

$$\frac{dP_1}{dt} = a_0 - a_1\cdot P_1, \tag{2}$$

where $a_0 = Q_H^T\cdot\left(\frac{V_0}{E}+\frac{F^2}{C}\right)^{-1}$, $a_1 = (\sigma + A)\cdot\left(\frac{V_0}{E}+\frac{F^2}{C}\right)^{-1}$.

Pressure P in pressure main is determined by the solution of (2):

$$P_1 = P_{01}\cdot e^{-a_1\cdot t} + \frac{a_0}{a_1}\cdot\left(1-e^{-a_1\cdot t}\right). \tag{3}$$

The rate of change of pressure is

$$\frac{dP}{dt} = -a_1\cdot P_{01}\cdot e^{-a_1\cdot t} + a_0\cdot e^{-a_1\cdot t}. \tag{4}$$

Leakage flow rate is

$$Q_y = A\cdot P_1$$

The volume of fluid spills from the hydraulic system is

$$V_y = \int Q_y\cdot dt$$

$$V_y = A\cdot P_0\int e^{-a_1\cdot t}\cdot dt + \frac{A\cdot a_0}{a_1}\int dt - A\cdot\frac{a_0}{a_1}\int e^{-a_1\cdot t}\cdot dt + C,$$

$$V_y = \frac{A\cdot P_0}{a_1}\cdot(1-e^{-a_1\cdot t}) + \frac{A\cdot a_0}{a_1}\cdot t - A\cdot\frac{a_0}{a_1^2}\cdot(1-e^{-a_1\cdot t}).$$

Numerical calculations are shown foe excavator ЭО – 4124:

$Q_H^T = 3000$ cm^3/s; $P_0 = 250$ kg/cm^2; $F = 200$ cm^2; $V_0 = 10000$ cm^3;
$E = 5000$ kg/cm^2; $\eta_H = 0{,}95$; $\sigma = 0{,}6$ cm^5/kg·s; $A = 119{,}4$ cm^5/kg·s; $a_0 = 882$ kg/cm^2·s;
$a_1 = 35{,}3$ $^1/_s$; $^{a_0}/_{a_1} = 25$ kg/cm^2.

With due regard to numerical values, equations are written as follows:

$$P_1 = 250\cdot e^{-35{,}3\cdot t} + 25\cdot(1-e^{-35{,}3\cdot t}), \tag{5}$$

$$\frac{dP_1}{dt} = -8825 \cdot e^{-35{,}3 \cdot t} + 882 \cdot e^{-35{,}3 \cdot t}, \tag{6}$$
$$Q_y = 119{,}4 \cdot P(t),$$
$$V_y = 845{,}6 \cdot (1 - e^{-35{,}3 \cdot t}) + 3000 \cdot t - 23{,}95 \cdot (1 - e^{-35{,}3 \cdot t}).$$

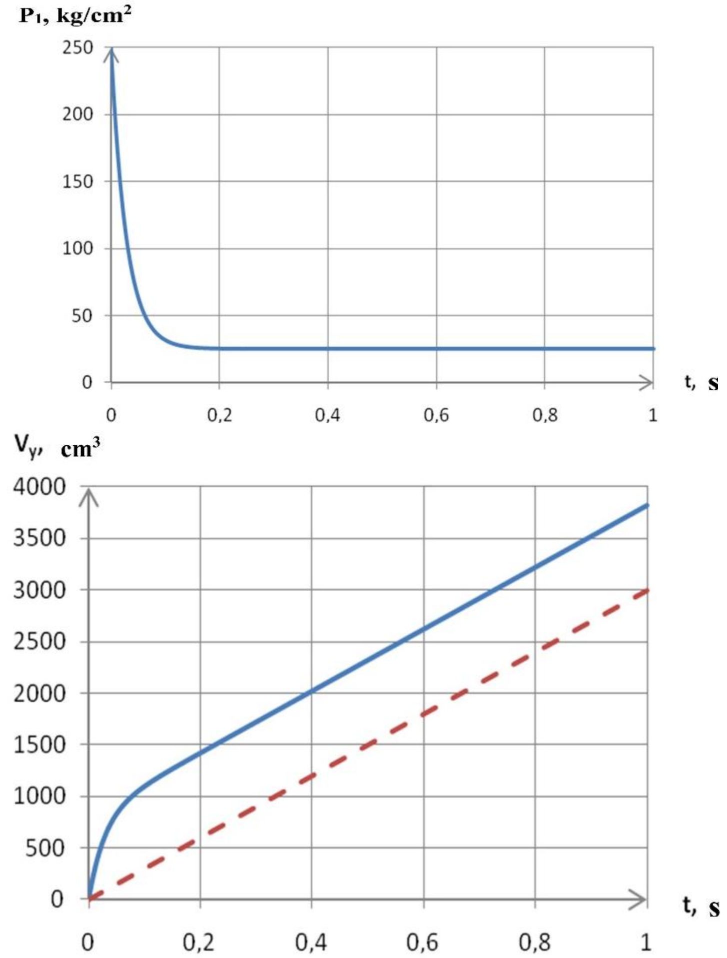

Figure 2. Transient curves for hydraulic system pressure line upon line rupture.

Calculation results show that pressure decrease processes take place momentarily (up to 0.1 second), and the rate of change of pressure can be an important information parameter for development of devices precluding significant losses of hydraulic fluid. Hydraulic fluid leak volume depends on pumping capacity and leakage time with due regard to the values of deformable volume of hydraulic system and hydraulic fluid.

In a drain line, the flow of hydraulic fluid through a return filter becomes disturbed at the moment of rupture in a pressure line. A hydraulic cylinder rod is displaced to the right side under the action of compressed spring force, and drain line fluid flow equation takes on the form of:

$$Q_f + Q_x = Q_{d.}, \tag{7}$$

where Q_f is hydraulic fluid flow rate through a return filter, cm^3/s,

$$\boldsymbol{Q_f = k \cdot P_2};$$

Q_x is a rate of hydraulic fluid flow due to the displacement of hydraulic cylinder barrel under the action of compressed spring force, cm^3/s,

$$Q_x = \dot{x} \cdot F_1;$$

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$$\boldsymbol{Q_d = -\frac{V_{02}}{E_2} \cdot \frac{dP_2}{dt}},$$

P_2 is the pressure in a drain line, kg/cm^3;
k is the factor of hydraulic fluid flow rate through a return filter, cm^5/kg·s;
$\dot{x}$ is a cylinder barrel displacement rate, cm/s;
Q_d is a flow rate determined by hydraulic fluid compressibility, cm^3/s;
V_2 is the hydraulic fluid volume in a drain line, cm^3;
E_2 is the drain line elasticity modulus, kg/cm^2.
Equation (7) can be expressed as

$$kP_2 - \frac{F \cdot F_1}{c} \cdot (a_0 - a_1 \cdot P_{01}) \cdot e^{-a_1 t} = -\frac{V_{02}}{E} \cdot \frac{dP_2}{dt}. \tag{8}$$

After transformations, derived (8) takes on the form of:

$$\frac{dP_2}{dt} + B_1 \cdot P_2 = -B_2 \cdot e^{-a_1 t}, \tag{9}$$

where $B_1 = k\frac{E_2}{V_{02}}$, $B_2 = \frac{E_2}{V_{02}} \cdot \frac{F \cdot F_1}{c} \cdot (a_1 \cdot P_{01} - a_0)$.

Solution for (5) is found in:

$$P_2 = \left(P_{20} - \frac{B_2}{a_1 - B_1}\right) \cdot e^{-B_1 \cdot t} + \frac{B_2}{a_1 - B_1} \cdot e^{-a_1 \cdot t}. \tag{10}$$

The rate of change of pressure is:

$$\frac{dP_2}{dt} = -B_1 \cdot \left(P_{20} - \frac{B_2}{a_1 - B_1}\right) \cdot e^{-B_1 \cdot t} - \frac{a_1 \cdot B_2}{a_1 - B_1} \cdot e^{-a_1 \cdot t}. \tag{11}$$

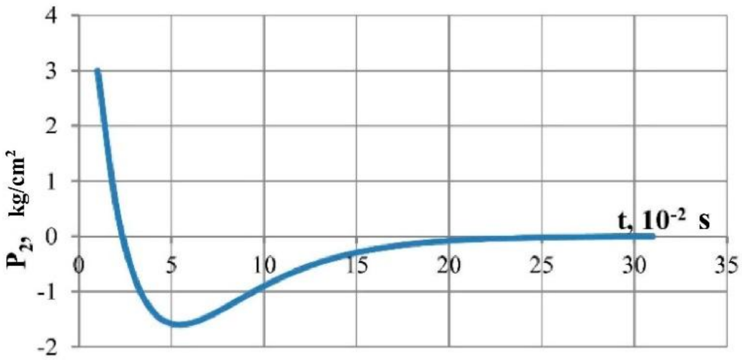
Calculations have been made for values of: $F = 200$ cm^2; $F_1 = 137$ cm^2;
$E_2 = 150$ kg/cm^2; $V_{02} = 5000$ cm^3; $P_{01} = 250$ kg/cm^2; k = 1000;
$a_1 = 35{,}3$ $^1/_s$; $P_{02} = 3$ kg/cm^2; $B_1 = 30$ $^1/_s$; c = 28500 kg/cm; $a_0 = 882$ kg/cm^2 · s; $B_2 = 229$ $^1/_s$.

With regard to numerical values, P_2 and $\frac{dP_2}{dt}$ take on the form of:

$$P_2 = 40{,}2 \cdot e^{-30 \cdot t} + 43{,}2 \cdot e^{-35{,}3 \cdot t}, \tag{12}$$

$$\frac{dP_2}{dt} = 1206 \cdot e^{-30 \cdot t} - 1524 \cdot e^{-35{,}3 \cdot t}, \tag{13}$$

Calculated values of (12, 13) are presented in Figure 3.



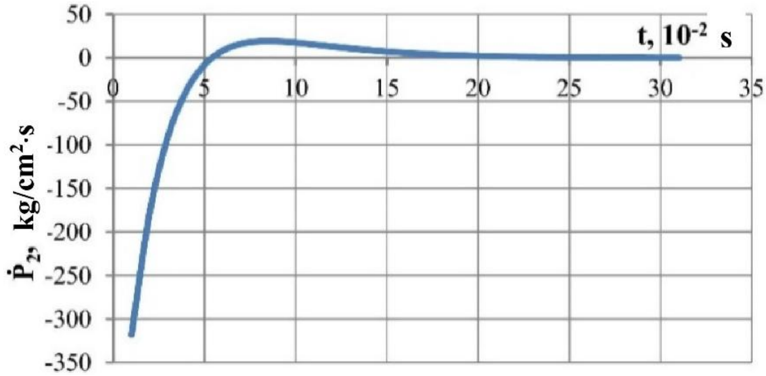


Figure 3. Transient curves for hydraulic system drain line upon line rupture.

3. Results

At the pressure line failure, the pressure in a drain line is likewise decreased sharply and cavitation phenomena can occur in the drain line [13, 20, 21, 23, 25, 26, 28].

Solution of (3, 4, 12, 13) shows that the rate of change of pressure in the drain line is significantly lower than in the pressure line. Therefore, the rate of change of pressure in the pressure line can be accepted as an information parameter for the development of a device acting, upon line rupture, to switch the flow of hydraulic fluid from the pump over to the tank for draining.

Modern hydraulic systems of mobile machines are equipped with pressure sensors in pressure and drain lines. There is no difficulty about refining upon a computer program to compute derivatives $\dot{P}$ and P_2, and a head-pilot valve assembly mounted at the pump output can actuate when limit values of information parameters are reached. Tests of the device manufactured under Author’s Certificate (USSR) No. 1492114 on excavator ЭО-4121A have shown that, when the plug valve mounted on the pressure line is opened, hydraulic fluid leaks do not exceed 0.5 dm^3.

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