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 \( P \) 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 \([5, 6, 7, 8, 9, 10, 11, 12]\):

\[
Q''_0 - \sigma \cdot P + \frac{V_0}{E} \frac{dP}{dt} + x \cdot F = Q_y,
\]

where \( Q''_0 \) is pump theoretical delivery, cm³/s;
\( \sigma \) is the pump leakage flow factor, cm³/kg·s;
\( V_0 \) is a volume of hydraulic fluid in pressure line, cm³;
\( E \) is the reduced modulus of elasticity of hydraulic fluid and hydraulic system, kg/cm²;
\( P \) is pressure, kg/cm²;
\( F \) is the rod area, cm²;
\( Q_y \) is a leakage flow rate, cm³/s.

Let’s express leakage factor as:
\[ \sigma = \frac{(1-\eta) \cdot Q_0}{P_H}, \]

where \( \eta \) is the hydraulic pump volume efficiency, \( \eta = 0.94 \ldots 0.96 \); \( P_H \) is normal pressure, kg/cm\(^2\).

Let’s write leakage flow rate \( Q_L \) in linearized form as:
\[ Q_L = \frac{\delta Q}{\delta P} \cdot P, \] or \( Q_L = A \cdot P \), cm\(^3\).

where \( A \) is a leakage factor, cm\(^3\)/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:
\[ Q_L = A \cdot P_{const}. \]

It can be assumed that the leakage flow is equal to the pumping capacity, then:
\[ A = \frac{Q_0 - \sigma \cdot P_{const}}{P_{const}} = \frac{Q_0}{P_{const}} \left[ 1 - \frac{P_{const}}{P_N} (1 - \eta) \right] \] or \[ A = \frac{Q_0 - \sigma}{P_{const}} \]

Let’s obtain rod displacement \( X \) under the action of elastic forces from:
\[ X = \frac{(P_0 - P) \cdot F}{C}. \]

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:
\[ \frac{dP_1}{dt} = a_0 - a_i \cdot P_1, \] (2)

where \( a_0 = Q_0 \left( \frac{V_0}{E} + \frac{F^2}{C} \right)^{-1} \), \( a_i = (\sigma + A) \left( \frac{V_0}{E} + \frac{F^2}{C} \right)^{-1} \).

Pressure \( P \) in pressure main is determined by the solution of (2):
\[ P_1 = P_{0i} \cdot e^{-a_0 \cdot t} + \frac{a_0}{a_i} \left( 1 - e^{-a_i \cdot t} \right). \] (3)

The rate of change of pressure is
\[ \frac{dP}{dt} = -a_i \cdot P_1 \cdot e^{-a_i \cdot t} + a_0 \cdot e^{-a_0 \cdot t}. \] (4)

Leakage flow rate is
\[ Q_L = A \cdot P_1 \]

The volume of fluid spills from the hydraulic system is
\[ V_y = \int Q_L \cdot dt \]

\[ V_y = A \cdot P_0 \int e^{-a_i \cdot t} \cdot dt + \frac{A \cdot a_0}{a_i} \int dt - A \cdot \frac{a_0}{a_i} \int e^{-a_i \cdot t} \cdot dt + C, \]

\[ V_y = A \cdot P_0 \cdot \frac{1}{a_i} \cdot (1 - e^{-a_i \cdot t}) + A \cdot \frac{a_0}{a_i} \cdot t - A \cdot \frac{a_0}{a_i} \cdot (1 - e^{-a_i \cdot t}). \]

Numerical calculations are shown for excavator ЭО – 4124:
\( Q_0^T = 3000 \text{ cm}^3/\text{s}; \ P_0 = 250 \text{ kg/cm}^2; \ F = 200 \text{ cm}^2; \ V_0 = 10000 \text{ cm}^3; \)
\( E = 5000 \text{ kg/cm}^2; \ \eta_{hl} = 0.95; \ \sigma = 0.6 \text{ cm}^3/\text{kg·s}; \ A = 119.4 \text{ cm}^2/\text{kg·s}; \ a_0 = 882 \text{ kg/cm}^2; \)
\( a_i = 35.3 \text{ cm}^3/s; \ \frac{a_0}{a_i} = 25 \text{ kg/cm}^2. \)

With due regard to numerical values, equations are written as follows:
\[ P_1 = 250 \cdot e^{-35.3 \cdot t} + 25 \cdot (1 - e^{-35.3 \cdot t}), \] (5)
\[
\frac{dP_1}{dt} = -8825 \cdot e^{-35.3 \cdot t} + 882 \cdot e^{-35.3 \cdot t}, \quad (6)
\]

\[
Q_y = 119.4 \cdot P(t),
\]

\[
V_y = 845.6 \cdot (1 - e^{-35.3 \cdot t}) + 3000 \cdot t - 23.95 \cdot (1 - e^{-35.3 \cdot t}).
\]

**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:

\[
Q_f + Q_x = Q_d, \quad (7)
\]

where \(Q_f\) is hydraulic fluid flow rate through a return filter, \(\text{cm}^3/\text{s}\),

\[
Q_f = k \cdot P_2;
\]

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

\[
Q_x = \dot{x} \cdot F_1;
\]
\[ \frac{dP_2}{dt} = \frac{V_{02}}{E_2} \cdot \frac{dP_2}{dt}, \]

\( P_2 \) is the pressure in a drain line, kg/cm³;
\( k \) is the factor of hydraulic fluid flow rate through a return filter, cm⁵/kg·s;
\( \dot{x} \) is a cylinder barrel displacement rate, cm/s;
\( Q_d \) is a flow rate determined by hydraulic fluid compressibility, cm³/s;
\( V_2 \) is the hydraulic fluid volume in a drain line, cm³;
\( E_2 \) is the drain line elasticity modulus, kg/cm².

Equation (7) can be expressed as
\[ kP_2 = \frac{F \cdot F_1}{c} \cdot (a_0 - a_1 \cdot P_0) \cdot e^{-at} = -\frac{V_{02}}{E_2} \cdot \frac{dP_2}{dt}. \]  

After transformations, derived (8) takes on the form of:
\[ \frac{dP_2}{dt} + B_1 \cdot P_2 = -B_2 \cdot e^{-at}, \]

where \( B_1 = k \frac{E_2}{V_{02}}, \quad B_2 = \frac{E_2}{V_{02}} \cdot \frac{F \cdot F_1}{c} \cdot (a_1 \cdot P_0 - a_0). \)

Solution for (5) is found in:
\[ P_2 = \left( P_{20} - \frac{B_2}{a_1 - B_1} \right) \cdot e^{-B_1 \cdot t} + \frac{B_2}{a_1 - B_1} \cdot e^{-a_1 \cdot t}. \]

The rate of change of pressure is:
\[ \frac{dP_2}{dt} = -B_1 \cdot \left( P_{20} - \frac{B_2}{a_1 - B_1} \right) \cdot e^{-B_1 \cdot t} - \frac{a_1 \cdot B_2}{a_1 - B_1} \cdot e^{-a_1 \cdot t}. \]

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

With regard to numerical values, \( P_2 \) and \( \frac{dP_2}{dt} \) take on the form of:
\[ P_2 = 40,2 \cdot e^{-30 \cdot t} + 43,2 \cdot e^{-35,3 \cdot t}, \]
\[ \frac{dP_2}{dt} = 1206 \cdot e^{-30 \cdot t} - 1524 \cdot e^{-35,3 \cdot t}. \]

Calculated values of (12, 13) are presented in Figure 3.
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 $P_1$ 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$^3$.

4. References
[1] AC No. 1492114 (USSR), IPC$^3$ E01H 5/12 Hydraulic system / G G Voskresensky, E N Lvov, A V Leshchinsky, A V Gurkov Appl. 08.04.88; publ. 30.12.89 Bul. 48 3
[2] Batorshin P V, Zenkov S A 1993 Study and testing of shut off valve of construction plant and equipment Shut-off valve study Proc. (Khabarovsk) pp 78-92
[3] Bashla T M 1971 Engineering hydraulics: Handbook Moscow: Mashinostroenie p 672
[4] Galdin N S 2007 Hydraulic and pneumatic systems: Electronic teaching guide Omsk: CDO SibADI 234 pp
[5] Galdin N S 2009 Hydraulic machines, fluid power drive: Teaching guide Omsk: SibADI 272 pp
[6] Galdin N S 2010 Fundamentals of hydraulics and hydraulic drive: Teaching guide Omsk: SibADI 145 pp
[7] Galdin N S 2005 Fundamentals of hydraulics and hydraulic drive: Electronic teaching guide Omsk: CDO SibADI 131 pp
[8] Galdin N S 2008 Components of mobile machine fluid power drives. Reference materials: Teaching guide Omsk: SibADI 127 pp
[9] Galdin N S, Kukin A V 2010 Collection of hydraulic schematics of mobile machines and equipment: Teaching guide Omsk: SibADI 91 pp
[10] Galdin N S, Semenova I A 2010 Hydraulic schematics of mobile machines: Teaching guide Omsk: SibADI 203 pp
[11] Artemiev T V 2005 Hydraulics, hydraulic machines and hydraulic pneumatic actuator: Teaching guide Moscow: Akademia 336 pp

Figure 3. Transient curves for hydraulic system drain line upon line rupture.
[12] Bashta T M 1982 Hydraulics, hydraulic machines and hydraulic drives: Textbook for universities Moscow: *Mashinostroenie* 423 pp
[13] Girgidov A D 2002 Fluid Mechanics: Textbook for universities Saint Petersburg: *SPbGPU* 545 pp
[14] Graedel T E 2004 Industrial ecology “Foreign textbook” series Moscow: *UNITY*
[15] Green N 1993 Biology in 3 volumes Moscow: *Mir*
[16] Zhenikhov Y N 2004 Hazardous waste handling: Teaching guid Tver: *TGTU* 224 pp
[17] Ignatov V G 2003 Ecology and economics of nature management Rostov-on-Don: Feniks, 512 pp
[18] Isidorov V A 2001 Ecological chemistry St. Petersburg: *Himizdat* 304 pp
[19] Galding N S, Efimenko I N, Rakhuba L F, Shokolova T N 2006 Concise Illustrated Russian-English Dictionary on Road Construction Machinery Omsk: *SibADI* 45 pp
[20] Lepeshkin A V, Mikhailin A A, Sheipak A A 2003 Hydraulics and hydraulic pneumatic actuator: Textbook Moscow: *MGIU* 352 pp
[21] Loitsyansky L G 2003 Fluid mechanics: Textbook for universities” Moscow: *Droda* 840 pp
[22] Novikov Y V 2003 Ecology, environment and human being Moscow: *FAIR-Press* 560 pp
[23] Popov D N, Panaiotti S S, Ryabinin V M 2002 Flow mechanics: Textbook for universities Moscow: *MGITU im. N.E. Bauman* 384 pp
[24] Smirnov Y N 1969 On calculation of automatic fail-close shutdown valve Moscow: *Nauka*, 293 pp
[25] Uginchus A A 2009 Hydraulics and hydraulic machines: Textbook Moscow: *Az-book* 395 pp
[26] Ukhin B V 2010 Hydraulics: Teaching guide Moscow: Forum, 464 pp
[27] Fomin N N, Makalin V S, Sizyntsev N E et al. 1990 Shut-off valve effect 10 pp 2-4
[28] Chugaev R R 2008 Hydraulics (Engineering fluid mechanics): Textbook Moscow: *Bastet* 672 pp