Simulation model of a hydro-impact system with two limiters of striker movement

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Abstract. A simulation model of a one-way self-oscillating hydro-impact system with two limiters of striker movement has been developed. The system includes a pump (a constant flow source), a striker (piston) and a housing (with limiters) connected by a mechanical spring, a spool valve, a gas-liquid accumulator, and connecting hydraulic lines. By comparing the results of calculations on the simulation model with the results of calculations on the ideal model (without hydraulic and mechanical losses and with instantly switching valve), the developed model was verified. Calculations of the working modes of reverse hydro-impact devices with an impact energy of 80 and 160 J were performed, their parameters were determined, and the real geometry of the devices was evaluated. The equipment being developed can be used to overcome jamming of equipment during drilling and using of special equipment in drilled holes, and driving holes by impact method in ground.

1. Introduction

Reversible hammers are used in mining and construction during drilling of holes in hard rock and performing technological operations in holes, driving pipes and forming holes in ground during trenchless laying of underground utilities, both to increase the speed of extraction of equipment from holes and to overcome jamming of the used equipment [1–4].

In [5], an ideal model of a reversible self-oscillating hydro-impact system with two limiters of striker movement, which is capable of producing impacts in forward and backward directions without structural changes in it, is considered. This peculiarity occurs when the parameters of the energy carrier change. In the model [5], only the main properties were considered, which made it possible to establish the existence of direct and reverse working modes at certain flow rates of the fluid.

The paper presents the simulation model of a reversible hydro-impact device taking into consideration a great number of properties of the system, such as valve operation, fluid properties, hydraulic and mechanical resistances, etc. The examples of calculating working cycles of the system for two sizes of a hydro-impact device are given.

2. Simulation model of a hydro-impact device with two limiters of striker movement

A schematic diagram of the system being investigated is shown in figure 1. The system includes a source of constant flow rate PU, an accumulator AC, a piston assembly (a striker P, a device housing F, anvils A1, A2, a spring S), a spool valve V, pressure 1 and drain 2 lines, pipes 7–10 connecting lines 1, 2 with hydraulic chamber 11 and control lines 3-6. The housing is assumed to be rigidly fixed.
The presented system works as follows. At the beginning of the working cycle, the striker P is on the anvil A2. When fluid is supplied to the pressure line 1, it flows through the control lines 6 and 5, 4, the groove 12 into the chambers of the spool valve 13 and 15. The spool V takes a left position, and the hydraulic chamber 11 is connected to the pressure line by channels 7, 8 through the groove 14 of the spool. The striker P moves to the left under the action of forces from a fluid in the chamber 11 and the spring S. The striker P reaches the \(-x_{P2}\) coordinate (a right edge of the groove 12 separates lines 4 and 5), then to the \(-x_{P1}\) coordinate (a left edge of the groove 12 connects the spool chamber 13 to the drain line 2 by lines 3 and 4). The spool V takes a right position, and the chamber 11 is connected to the drain line 2. The striker P moves under the action of only spring force. During this phase, the striker slows down and can impact upon the anvil A1. After stopping the striker, it moves to the right. When the striker P reaches the coordinates \(-x_{P1}\) and \(-x_{P2}\), the control line 4 is separated from the drain line 2 and connected to the pressure line 1. The spool V returns to a left position and the chamber 11 is connected to the pressure line 1. The striker V slows down and can impact upon the anvil A2. After stopping the striker, it moves to the right and the working cycle repeats.

To develop a simulation model of the system, we used algorithms and equations described in [6-7] and a program [8]. The mathematical description of the simulation model includes a system of differential-algebraic equations, which includes equations of dynamics of the striker, the spool and the gas-liquid accumulator.

According to Newton's theory, the movement equation for the striker is described as follows:

\[
\frac{dx_P}{dt} = v_P, 
\]

\[
m_P \frac{dv_P}{dt} = -S_{p11}p_{11} - c_m (x_p + x_3) - (k_{p11}p_{11} + k_{p13}p_3) \text{sgn}(v_P),
\]
where $x_P$, $v_P$ are the displacement and velocity of the striker; $m_P$ is the mass of the striker; $S_{P11}$ is the striker area from the side of the chamber 11; $p_{11}$, $p_3$ are the seals pressure; $k_{P11}$, $k_{P3}$ are the coefficients determining the friction force in seals; $c_{m}$, $x_3$ are the spring stiffness and pre-compression.

The movement equation for the spool is described as follows:

$$\frac{dx_v}{dt} = v_v,$$

$$m_V \frac{dv_v}{dt} = -S_{v13} p_{13} + S_{v15} p_{15} - (k_{v13} p_{13} + k_{v15} p_{15}) \text{sgn}(v_v),$$

where $x_v$, $v_v$ are the displacement and velocity of the spool; $m_V$ is the mass of the spool; $S_{v13}$, $S_{v15}$ are the spool areas from the side of the chambers 13 and 15; $p_{13}$, $p_{15}$ are the seals pressure equivalent to the pressure in the chambers 13 and 15; $k_{v13}$, $k_{v15}$ are the coefficients determining the friction force in seals.

The dynamics of the accumulator is described by the equation of polytropic process in the gas cavity:

$$\frac{dp_A}{dt} = \gamma \frac{p_{10}^{\gamma - 1} V_n}{p_n^{\gamma - 1} V_n} q_{10},$$

where $p_A$ is the accumulator pressure; $q_{10}$ is the flow rate to the accumulator; $p_n$, $V_n$ are the pre-fill pressure and volume of the accumulator; $\gamma$ is the polytropic exponent of gas in the accumulator.

The equations of fluid flow in the pressure 1 and drain 2 lines, pipes 3–15, local resistances (throttles, bends, compression of fluid), tees are described in [6] [9].

The flow rate in the pressure line is described by the equation:

$$q_1 = q_0 - \frac{p_1}{r_0},$$

where

$$r_0 = p_n / [q_0 (1 - \eta_0)],$$

where $p_n$, $\eta_0$ are nominal pressure and volumetric efficiency of a pump.

The impact was considered instantaneous, and velocities after impact were calculated from the relations of the impact theory:

$$v_{P-} = -R v_{P+},$$

$$v_{V-} = -R v_{V+},$$

where $v_{P+}$, $v_{P-}$ are the velocities of the striker and spool before impact; $v_{V+}$, $v_{V-}$ are the velocities of the striker and spool after impact; $R$ is the velocity recovery factor.

The initial conditions (coordinates and velocities of mechanical elements, pressures and flow rates in pipes of the system at $t = 0$) were set as follows:

$$x_p(0) = v_p(0) = x_v(0) = v_v(0) = 0,$$

$$p_i(0) = p_{A,i}, i = 1\ldots15,$$

$$q_i(0) = q_0 - p_{A,i}/r_0,$$

$$q_i(0) = 0, i = 2\ldots15.$$
Separation and connection of the pipelines, which provides an auto-oscillatory working cycle of the device, in the program is realized by changing the areas of the corresponding local resistances connecting these pipelines.

The simulation program is written in the object-oriented C ++ language. The numerical procedure is implemented using Runge-Kutta method with Egorov's control term. The local accuracy of calculations was taken equal to $5 \cdot 10^7$.

3. Example of calculation of the hydro-impact system’s limit cycles and results analysis

Calculations were performed for the following system parameters:

- nominal pressure $p_n$ 14 MPa
- pump volumetric efficiency $\eta_0$ 0.7
- fluid flow rate $q_0$ $5.0 \cdot 10^{-5} \div 20.0 \cdot 10^{-5}$ m$^3$/s
- striker mass $m_p$ 2.2 kg
- striker area from the side of the chamber 1 1 $S_{11}$ 2.14 $\cdot 10^{-4}$ m$^2$
- coordinate $x_{1[1]}$ 0.04 m
- coordinate $x_{1[2]}$ 0.02 m
- maximum striker stroke $x_{1[4]}$ 0.06 m
- spring stiffness $c_m$ 6.35 $\cdot 10^3$ N/m
- spring pre-compression $x_3$ 0.02 m
- spool mass $m_V$ 0.3 kg
- coordinate $x_{1[1]}$ 0.003 m
- maximum spool stroke $x_{1[4]}$ 0.006 m
- velocity recovery factor $R$ 0
- accumulator pre-fill pressure $p_n$ 1.0 MPa
- accumulator volume $V_n$ 25.0 ml
- diameter of pressure 1 and drain 2 lines $d_{1,2}$ 0.014 m
- diameter of pipelines 3–6 $d_{3,6}$ 0.008 m
- diameter of pipelines 7–10 $d_{7,10}$ 0.01 m

Figures 2–4 show theoretical oscillograms of dynamic characteristics of limit cycles obtained at different fluid flow rates $q_0$: displacement $x_P$ (a) and velocity $v_P$ (b) of the striker, accumulator pressure $p_A$ (c) and spool displacement $x_V$ (d). When the fluid flow rate $q_0 = 6.1$ l/min, there is a mode with impacts in forward direction. When the fluid flow rate $q_0 = 10.2$ l/min, there is a mode with impacts in forward and backward directions. When the fluid flow rate $q_0 = 14.3$ l/min, there is a mode with impacts in backward direction.

Figure 2. Theoretical oscillograms of dynamic characteristics at the source flow rate $q_0$ = 6.1 l/min: $x_P$, $v_P$ – displacement and velocity of the striker; $p_A$ – accumulator pressure; $x_V$ – spool displacement.
Figure 3. Theoretical oscillograms of dynamic characteristics at the source flow rate $q_0 = 10.2$ l/min: $x_p$, $v_p$ – displacement and velocity of the striker; $p_A$ – accumulator pressure; $x_V$ – spool displacement.

Figure 4. Theoretical oscillograms of dynamic characteristics at the source flow rate $q_0 = 14.3$ l/min: $x_p$, $v_p$ – displacement and velocity of the striker; $p_A$ – accumulator pressure; $x_V$ – spool displacement.

For comparison, the dashed lines in the figures show oscillograms of the dynamic characteristics of the device, calculated using the ideal model, which takes consideration only the main properties of the system [5]. A feature of this ideal model is the unavailability of a spool valve and friction forces. It was believed that the valve switches instantly and without energy consumption. Therefore, the fluid flow rate was reduced by an amount corresponding to the fluid consumption for its work. And also, the separation of chamber 11 from the pressure line 1 and the connection with the drain line 2 did not occur when the edges of the striker crossed the coordinates $x_{P1}$ and $x_{P2}$, but at the moments at which the spool passed the average position, at which there was a real change in a direction of fluid flows.

Comparing the results of the calculations, it can be noted that, in general, the dynamics of the working cycles is sufficiently well repeated both qualitatively (at the same values of $q_0$, identical working modes of the device are observed) and quantitatively (the difference in the values of characteristics does not exceed 10%). The increase in the discrepancy when the flow rate and therefore pressure in the system increases is possibly due to an incorrect choice of the parameter defining the volumetric leakage in the system in the ideal model. Also, in the calculations using the ideal model, the pressure fluctuations during the working cycles are much higher than in the calculations using the simulation model. This may be due to significantly higher hydraulic stiffness of the system in the first case, as in the simulation model relatively large volumes of fluid were introduced into the model, not considered in the first case.

4. Conclusions
A simulation model of a reversible hydro-impact device has been developed. The developed simulation model allowed to investigate properties of the system when model parameters and external conditions change. Test calculations have allowed to establish the peculiarities of dynamics of the hydro-impact device and possibility of realization of various working modes, depending on fluid supply.

The comparison of the calculation results of the developed simulation model with the calculation results of the ideal model, which takes into consideration only the main properties of the system,
allowed to a certain extent to verify the simulation model. Satisfactory qualitative and quantitative agreement of the results was obtained.

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