The Dynamic Behavior of the Flow in the Pipeline with Oil

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Abstract: The article deals with dynamic flow behaviour in oil piping, modulus of fluid elasticity and its influence on the dynamic behaviour of hydraulic systems. In this paper, a methodology is to model the unsteady flow. Mathematical modeling of the measured pressures is implemented on the basis of the boundary conditions and is carried out in program Matlab SimHydraulics. The comparison results are in agreement.

Keywords: *hydraulic hammer, simulation, unsteady flow, modulus of fluid elasticity, oil.*

1. Introduction

Mathematical - physical modeling is based on the application of the laws of physics. They can be used to create mathematical models of mechanical, hydraulic, pneumatic, electrical and thermal systems. The simulation is consisted in creating a simulation mathematical model and its solution.

Hydraulic fluid elastic modulus

The modulus of elasticity has a very important role in the calculations and affects the dynamics of hydraulic systems. It depends on pressure, temperature and the amount of dissolved air. The amount of air in the oil has the greatest impact on value of the modulus of elasticity, as the air is much more compressible. Its theoretical value for mineral oil is in the range of $K = (1.4 - 1.8) \cdot 10^9$ Pa [7, 8]. Measurement of modulus of elasticity is poorly realizable especially in operating conditions, so its value is determined laboratory or estimated. In this work, the modulus of elasticity is determined from the wavelength and consequently by the sound velocity in the hydraulic hammer. However, this modulus of elasticity is determined as time independent of pressure. This affects the accuracy of the calculation. [3, 5, 9]

The dynamics of the two-stage indirect-controlled valve

Reducing two-stage indirectly controlled valve has a pressure control function in the circuit - the safety valve. Generally, these valves are used to reduce higher pressures p and flow rates Q. Its scheme is shown in Fig. 1.

Equations describing the dynamics of the reducing valve are given by the following relations. The valve is closed at $x = x_m$ and fully opened at $x = 0$. At the node with pressure p_2 the following linearized equations apply

$$Q_5 = Q_3 + Q_4$$
$$Q_3 = \frac{(p - p_2)}{R_1}$$
$$Q_4 = Q_2 = Sv = S\frac{dx}{dt} \qquad (1)$$
$$Q_5 = \frac{(p_2 - p_r)}{R_2}$$

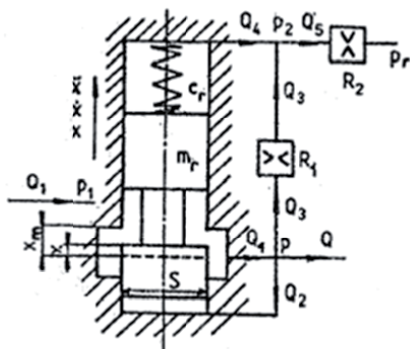*** Corresponding author:** Jana Jablonská, **E-mail address:** *jana.jablonska@vsb.cz*

Fig. 1: *Diagram reducing indirectly controlled valve (p – pressures, Q - flow rates, R - resistive). [2]*

The motion equation of the valve spool is [2]

$$m_r \frac{d^2x}{dt^2} + \left(b_r S^2 \frac{R_1 \cdot R_2}{R_1 + R_2}\right)\frac{dx}{dt} + c_r x = \\ = (p - p_1)S\frac{R_1}{R_1 + R_2}$$

(2)

Where m_r - mass of the spool valve, b_r damping coefficient, c_r spring constant, S surface of the spool valve.

In Matlab SimHydraulics, a differential equation of the first order is used, so equation (2) is divided by the mass of the spool valve and the first member (second derivative) is not considered in the equation. The equation after this mathematical adjustment has the following shape

$$\frac{\left(b_r S^2 \frac{R_1 R_2}{R_1 + R_2}\right)}{m_r}\frac{dx}{dt} + \frac{c_r x}{m_r} = \frac{(p - p_1)S}{m_r}\frac{R_1}{R_1 + R_2}$$

(3)

The equations can be solved numerically for labeled flows and displacement x at the given pressure. The necessary constants are determined from the experimental measurements of transient characteristics [2].

Mathematical modeling

The modeling of hydraulic circuit elements consists in assembling mathematical models to allow computation of pressure and flow values at individual points in the circuit. The method of electrical analogy of hydraulic resistances is used for definition of mathematical models of hydraulic elements An electrohydraulic analogy allows the examination of hydraulic elements, their groups and systems by investigation methods applied on electrical circuits whose transient properties are comparable [2]. Based on the analogy of hydraulic parameters (p, Q) and electrical parameters (U, i) the resistances are defined [2-4]:

Hydraulic resistance to motion represents friction and local resistances in flowing fluid

$$R = \frac{d(\Delta p)}{dQ}$$

(4)

Hydraulic resistance to acceleration (hydraulic inductance) from the mechanical point of view, it is the influence of mass inertia. The reason of resistance to acceleration is inertia of the fluid or inertia of a moving mass (piston, piston rod, spring, etc.). [2].

$$L = \frac{\Delta p}{\frac{dQ}{dt}}$$

(5)

Hydraulic capacity represents the inverse value of resistance to deformation (fluid, gas, pipes, springs, etc.) [2].

$$C = \frac{Q}{\frac{d(\Delta p)}{dt}}$$

(6)

2. Hydraulic hammer measurement

Fig. 2 shows the circuits on which the hydraulic hammer measurements have been made. In variant A there is displayed the circuit with a toothed flowmeter located between the valves. The toothed flowmeter represents a local resistance in the hydraulics circuit, therefore it has been replaced by clamp-on flowmeter, see version B. In the hydraulics circuit the hydraulic oil VG 46 at the temperature 26°C flows.

Hydro-generator HG1 pumps the liquid from the main tank T1 to the circuit and it is powered by electric motor M1. The circuit is protected against overload by the safety valve SV (two-stage indirectly controlled reducing valve). On the tank T1 is placed measuring cube MC, on which the pressure p_1 is measured. The toothed flowmeter TFM is located between ball valves BV1 and BV2 (variant A). Behind the flowmeter there is a T-piece with parallel connected nozzle and a closed ball valve. Tested horizontal pipeline is connected between valves YV1 and YV2 with the circuit. These valves are electrically controlled and equipped
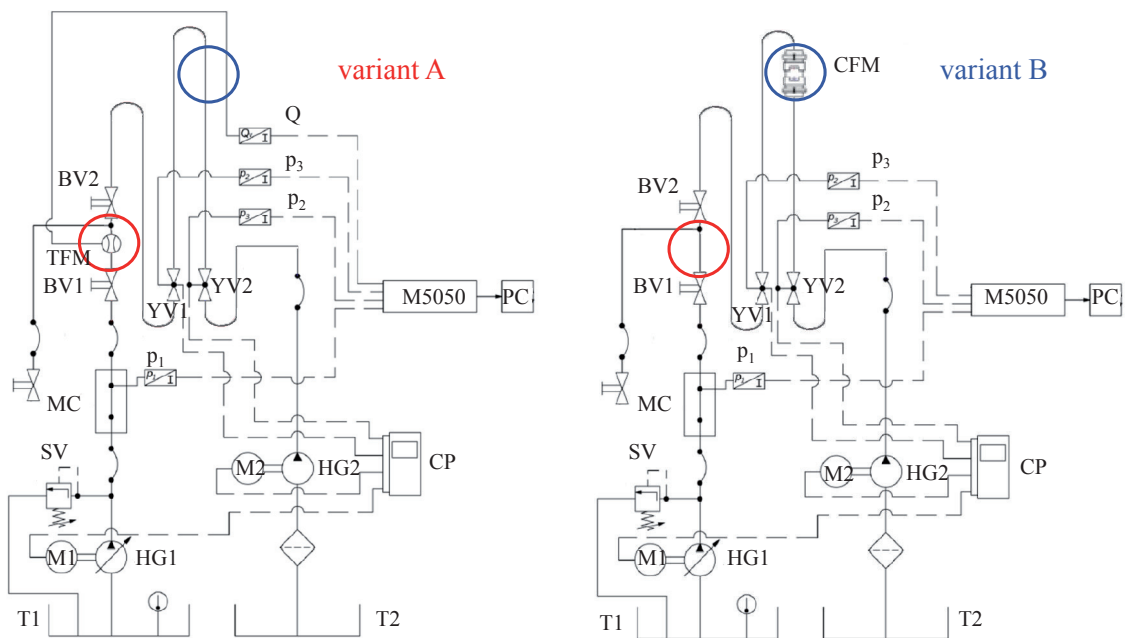
Fig. 2: *Circuit diagram for measuring of hydraulics hammer.*

with pressure sensors p_2 and p_3. Between valves YV1 and YV2 there is the clamp-on flowmeter CFM located, see variant B. The end of the horizontal pipeline is connected to a rubber hose leading to tank T2. This tank serves only as a fluid collection. Hydro-generator HG2 serves only to pump the liquid from tank T2 to tank T1. The valves YV1 and YV2 and the hydro generators HG1 and HG2 are controlled by the control panel CP.

The signals from pressure sensors are recorded in the Hydrotechnik M5050. The measurement record is set to 10 s with the sampling frequency 1000 Hz. The pressure sensors p_1, p_2, p_3 have a range $(0 \div 60)$ bar and an accuracy $\pm 0.5\%$. The flow measured on toothed flowmeter is also recorded in the Hydrotechnik M5050. The toothed flowmeter has a range $(0.7 \div 70)$ dm³.s⁻¹ and an accuracy $\pm 0.5\%$. The bi-directional non-invasive ultrasonic flowmeter has range of flowrate, resp. velocity in range $(0.1 \div 20)$ m.s⁻¹ and accuracy is $\pm 3\%$ for tube diameter $(13 \div 75)$ mm at velocity greater 0.2 m.s⁻¹.

Flow control is performed by tilting the hydro-generator plate. Hydro-generator parameters are: theoretical geometric volume $V_g = 51.22$ cm³, nominal flow $Q = 63$ dm³.min⁻¹. The safety valve (two-stage, indirect controlled) is controlled by a hand wheel.

The YV1, YV2 valves have a very fast response. Fig. 3 shows the shut-off time of the valve at given flow rate (for $Q_A = 9.048$ l.min⁻¹ is $t_{uz} = 59$ ms, for $Q_B = 17.04$ l.min⁻¹ is $t_{uz} = 49$ ms).
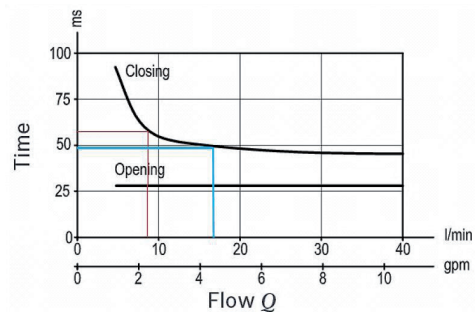

Fig. 3: *Determination of shut-off time for YV1 and YV2. [1]*

3. Evaluation of the hydraulic hammer measurement by closing the valve YV1

Measured pressure curves and period definitions needed to calculate fluid elasticity modulus K in hydraulic hammer are presented in Fig. 4. To determine the sound velocity in the fluid, it is also necessary to know the distance between the pressure source and the closing point ($l = 9.65$ m).
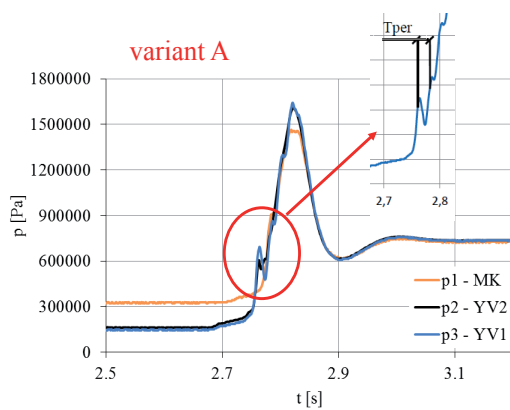
Fig. 4: *Pressure curves at hydraulic hammer - variant A, B.*

The mean values of steady state pressures are shown in Tab. 1. The pressure p_1 (variant A) measured on the measuring cube MK is higher by approximately 200 kPa than the pressure p_1 (variant B) measured in circuit with the toothed flowmeter. The pressures p_2 and p_3 (variant A) are measured on the valves and they are approximately about 100 kPa higher at a double flow rate (variant B).

In Tab. 2 there are calculated basic parameters of hydraulic hammer, which are subsequently used for simulation.

Tab. 1: *Average measured values of pressures and flow rate at steady state measured before closing of valve.*

		Variant A	Variant B
Pressure on measuring cube	p_1 (kPa)	327	532
Pressure on valve YV1	p_2 (kPa)	162	265
Pressure on valve YV2	p_3 (kPa)	147	236
Flow rate	Q (m3.s⁻¹)	0.00015	0.00028

Tab. 2: *Calculation of basic parameters of hydraulic hammer.*

		Variant A	Variant B
Period	T_{per} (s)	0.023	0.021
Wave run time	T_{bv} (s)	0.015	0.0105
Speed of the sound in the liquid	a_s (m.s⁻¹)	1678.3	1838.1
Flow velocity	v (m.s⁻¹)	0.48	0.9
Modulus of fluid elasticity	K (kPa)	$2.45 \cdot 10^6$	$2.94 \cdot 10^6$
Reynolds number	Re (1)	126	237
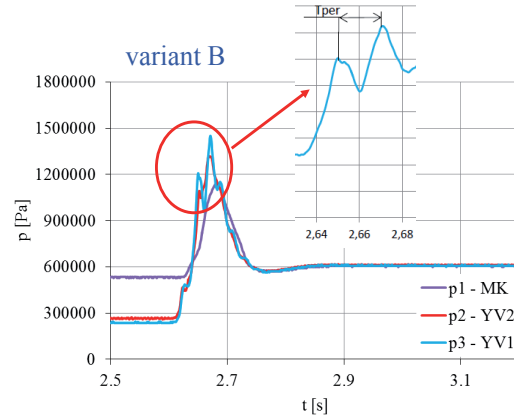
4. Mathematical model of hydraulic circuit

The mathematical model of the hydraulic circuit for hydraulic hammer measuring was created in the Matlab - Simulink program, using the SimHydraulics library, see Fig. 5.

Block of variable orifice represents valves YV1 and YV2, which is specified by parameterization of maximum flow area and opening. For this parameterization, it is only necessary to calculate the maximum flow area of the valve $S_{max} = 3.15 \cdot 10^{-4}$ m² and estimate the flow coefficient, see Tab. 3.

Tab. 3: *Flow coefficient of valves YV1 YV2 for individual variants.*

		Variant A		Variant B	
		YV1	YV2	YV1	YV2
Flow coefficient	(1)	0.0275	0.025	0.04	0.041

5. Conclusions - Evaluation and comparison of simulation of hydraulic hammer with measurement

The article deals with simulation of hydraulic hammer in oil flow at relatively low pressure (low pressure hydraulic system). Dynamics of flow is significantly influenced by the fluid elasticity modulus (oil), therefore it is necessary to deal with its precise determination depending on the pressure. Mathematical models of dynamic behaviour of flow were time-dependent, one-dimensional, solved in Matlab SimHydraulics. Two variants of the hydraulic circuit were tested. In Variant A, a toothed flowmeter (local resistance) was connected to the circuit. In variant B, the toothed flowmeter was replaced by a pipeline, and the flow was measured by an ultrasonic flowmeter that does not exhibit any
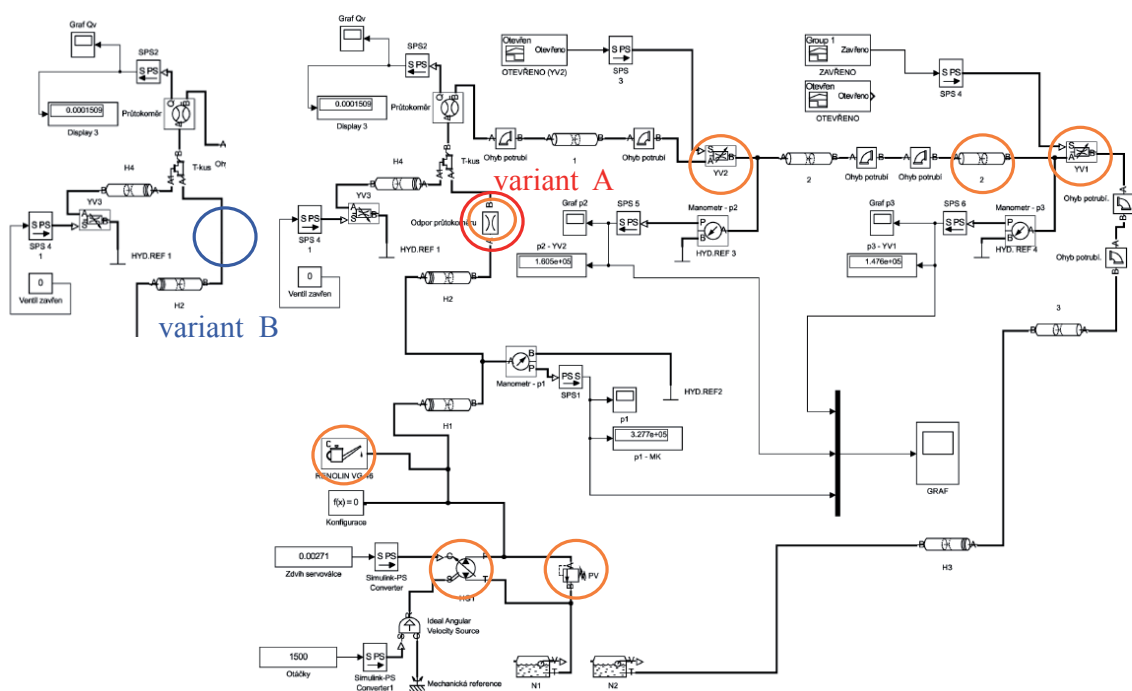
Fig. 5: *Mathematical model of the circuit for the hydraulic hammer measurement (red - variant A, blue - variant B, orange - elements further specified).*
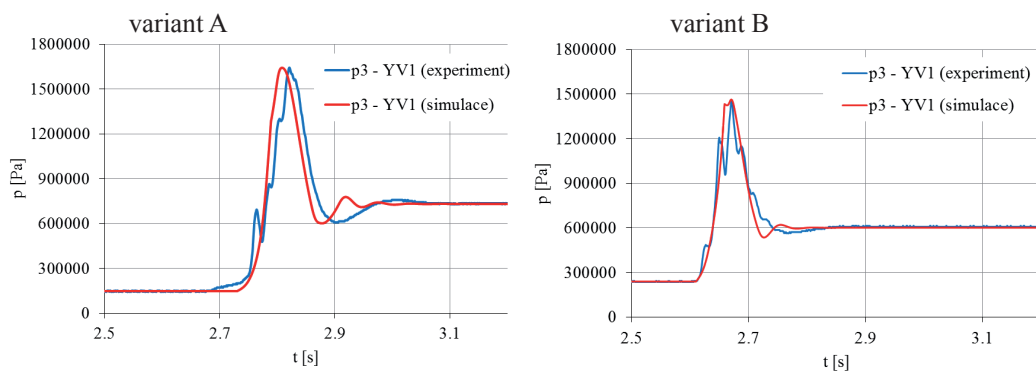

Fig. 6: *Comparison of hydraulic hammer simulation with measurement.*

resistance in the pipeline.

The modeled pressure curves for both variants (A, B) have approximately the same pressure peaks in simulation and measurement. For both variants, the simulated pressure curves are much smoother than measured. They differ slightly in the period (simulation period is smaller than the measured one).

In conclusion, one-dimensional simulation modeling (Matlab SimHydraulics) is well suited to measurement. The one-dimensional modeling method is relatively simple. All constants can be determined from the catalog sheets of individual hydraulic elements, or supplemented by measurement of static characteristics. The oil properties (density, modulus of fluid elasticity and kinematic viscosity) can be determined at a given temperature and pressure. In the article the

modulus of fluid elasticity is determined from the measurement and other quantities from literature [6, 10]. For the two-stage indirect-controlled reduction valve (safety valve), it is necessary to consider the dynamics of the valve spool movement. Method of mathematical modeling allows you to simulate the dynamics of newly designed hydraulic circuits.

6. Acknowledgment

References and Notes

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