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SIMULATION OF HYDRAULIC CIRCUITS IN AN INTELLIGENT PROGRAMMING ENVIRONMENT (PART 2)

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Abstract: *The paper discusses computing steady state conditions and transient responses of hydraulic circuits of fluid power system in the visual programming environment CoCoViLa. Multi-pole mathematical models for hydraulic circuits have been discussed in the paper "Simulation of Hydraulic Circuits in an Intelligent Programming Environment (Part 1)". The CoCoViLa environment used for simulation is a visual programming tool, which supports declarative programming in a high-level language and automatic program synthesis. The implemented modelling and simulation system enables one easily to describe and calculate characteristics of various complicated hydraulic circuits used in fluid power systems.*

Key words: hydraulic circuit, multi-pole model, CoCoViLa programming environment, graphical problem description, automatic program synthesis.

1. INTRODUCTION

The aim of the current research is to make the computer simulation of hydraulic circuits easier, more precise and faster, which is important when simulating large and complicated fluid power systems.

A modelling and simulation system is proposed for simulating steady state conditions and dynamic transient responses of hydraulic circuits. A visual programming environment CoCoViLa is used as a tool.

Fundamentals of model construction principles and methods have been described in papers by Grossschmidt and Harf [1, 2]. The special features of the used approach are as follows:

- Using visual programming and automatic program synthesis for composing and solving simulation tasks.
- Using multi-level distributed calculations enabling to avoid solving large equation systems.

Using proposed methods in modelling and simulation of a load-sensing fluid power system have been discussed in a paper by Grossschmidt and Harf [3].

2. SIMULATION OF HYDRAULIC CIRCUITS

2.1 Classes of hydraulic circuits

The following component classes are defined:

- tubes **TubeG, TubeH, TubeY, TubeZ**;
- dead end tubes **Tubeg, Tubeh**;
- local resistors **ResG, ResH, ResY**;
- volume elasticities **VeZ**;
- hydraulic interface elements **IE**;
- basic properties of fluids **Fluid**.

Calculations of hydraulic resistors and tubes characteristics at every step of calculation are described in class **Flow**:

- physical properties of the fluid (density ρ, viscosity ν and compressibility factors β_A and β_F) depending on the temperature θ and the arithmetical medial pressure at the ports of the hydraulic circuit element $p = (p1 + p2)/2$;
- flow resistances ***Rl*** and ***Rt,*** fluid inertia ***L*** and volume elasticity ***C*** of tube;
- values ***Rl*** and ***Rt*** for various local hydraulic resistances (**RRa** - round channel, **RRb** - circular axial slot, **RRc** - round orifice, **RRd** – not round orifice, **RRe** - local hydraulic resistance, **RRg** -

hydraulic device with linear resistance, **RRh** - hydraulic device with square resistance).

The classes ***static Simulation*** *and* ***dynamic Simulation*** are used for the computing process organization.

2.2 Computing process organization

Using visual specifications of described multi-pole models one can graphically compose a number of specifications (models) of various hydraulic circuits. Using the specific feature of the CoCoViLa environment [4] – automatic program synthesis, it is easy to solve various computing problems on each fluid power system. The simulation process includes calculations of steady state conditions and dynamics.

Initial values of pressures and volumetric flows for calculations must be specified. Results of calculations of steady state conditions (pressures and volumetric flows) are used as initials for dynamic calculations as well.

Transient responses caused by disturbances are calculated in the dynamic simulation. Disturbances are considered as changes of pressures or volumetric flows in inputs of the hydraulic circuit. Disturbances of different shapes are considered, such as constant, step, impulse, sine, linear, etc. Calculations of dynamic responses are performed in time. The time step length and number of steps must be specified.

To follow the system behaviour in time, the concept of state is invoked. State is introduced as a couple of variables, characterizing the system at certain moment of time (at certain time step).

Dynamic calculations proceed from the initial state to the final state. The key procedure here is the procedure of computing the next state values from the (known) current state (or several previous states as well) values.

All the computing procedures are automatically synthesized from the visual specifications by the CoCoViLa program synthesizer.

Using multi-pole models allows separating inner and outer variables of components. All the variables described in a multi-pole model of the component are as inner variables. Variables that are multi-pole model poles are outer variables of the component as well. Outer variables can be used both in the component model and outside.

The models of components may be very large and sophisticated. They may include the conditional dependences, iteration and integration procedures, etc.

Using multi-pole models allows perform calculations at two separate levels:

- at the lower level are those which take place in every component model between inner variables of the component;
- at the higher level are those which take place in the model of the whole hydraulic circuit and include only outer variables of components.

The model of the fluid power system is built up from multi-pole models of components by connecting necessary poles. When analyzing the fluid power system models one can see that loop dependences can appear between outer variables of components. The special iteration procedure has been used for solving these loop dependences. Usually we split the potential variables which are as outputs of the multi-pole models of components. The re-computing algorithm for each splitted variable is automatically synthesized by the CoCoViLa system. Results of calculations of steady state conditions are used as initial values in iterative recomputing.

3. SIMULATION EXAMPLES

3.1 Transient responses in the tubes

In this chapter, simulation examples of tube dynamics are considered. Most adequate for describing hydraulic tubes dynamics are models with distributed parameters [1]. Approximate models of such kind can be considered consisting of a couple of similar models with lumped parameters. In this way we take into account several natural frequencies of the tube.

The following parameter values are used in all the simulation examples under consideration (except tube lengths l and number of tubes n).

For the fluid HLP46**:** cinematic viscosity at temperature 40^0C ν_{40} = 46E–6 m^2/s, density at temperature 15^0C ρ_{15} = 875 kg/m^3, basic compressibility factor of fluid at temperature 20^0C β_{F20} = 1/18.4E8 m^2/N , relative content of undissolvable air in fluid vol = 0.02 and temperature $\theta = 40^0$C.

For the tubes**:** inner diameter d = 0.019 m, wall thickness s = 0.003 m and bulk module of the tube material K = 2.1E11 N/m^2.

Flow parameters**:** coefficient of hydraulic friction at laminar flow Al = 75, coefficient of hydraulic friction at turbulent flow λ = 0.04 and local resistance coefficient $\zeta = 2$.

Coefficient of adjusting the damping in the dynamic process: kr = 1.5.

Computing parameters**:** inverse value of the time step τ = 1E5 1/s.

Simulated graphs in all the examples are organized as follows. Curves 1 and 2 represent disturbances applied to the circuit, curves 3 and 4 represent simulation results.

In the example (Fig. 1) simulation of transient responses of a tube consisting of 7 sequential tubes, presented by four-pole models of form G, is considered.

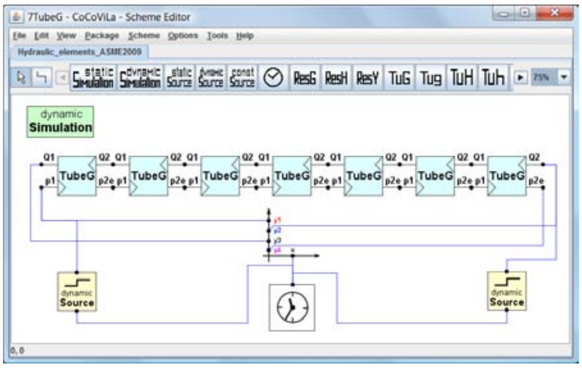

Fig. 1. Simulation task of the hydraulic circuit, represented by 7 tube models of form G

A step disturbance of pressure at the left port of the circuit and a constant volumetric flow at the right port of the circuit (dynamic Sources) are applied as inputs. A clock for the time is used.

Graphs of the transient response of outputs at the left and right port of the circuit (Fig. 1) are shown in Fig. 2.

Tube length**:** length of one tube model l = 2 m, n = 7 (total length of the circuit 14 m).

Disturbance parameters: pressure step disturbance at the left port (1): constant initial value $mean$ = 5E6 Pa, step value $step$ = 1E6 Pa, disturbance duration t = 5E-4 s;

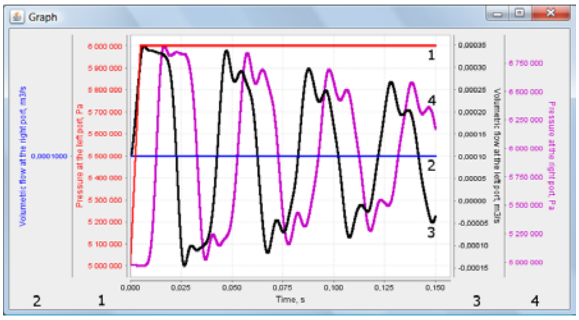

Fig. 2. Graphs of the transient response of variables at the left and right port

constant volumetric flow at the right port (2): $mean$ = 1E-4 m^3/s.

Fig. 2 shows that the computed graphs (3, 4) are influenced by oscillations with higher frequences.

Graphs of the transient response of outputs at the left and right port of the circuit in case number of tube models n = 28 and length of one tube model l = 0.5 m, (total length of the circuit 14 m) are shown in Fig. 3.

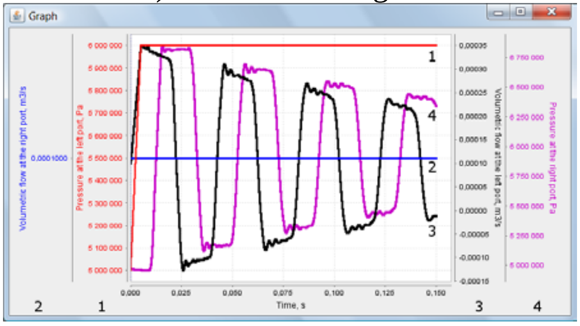

Fig. 3. Graphs of the transient response of variables at the left and right port

When simulating larger fluid power systems it is reasonable to use the tube model as simple as possible. In the following example the model consisting of one tube model form G (taking into account the first natural frequency of the tube), is used. The simulation results are shown in Fig. 4.

Fig. 4 shows that the graphs (3, 4) have the same natural frequency, amplitudes and damping as the processes in tasks 7TubeG (Fig. 2) and 28TubeG (Fig. 3).

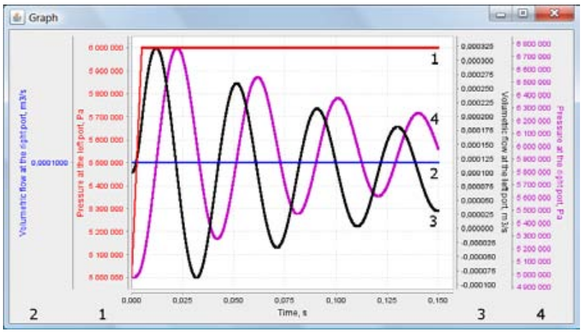

Fig. 4. Graphs of the transient response of variables at the left and right port

Using silencers at the ends of the tube allows reducing vibrations in the tube. Silencers considered in our examples consist of a sequentially connected local hydraulic resistor and dead end tube. Simulation task of the tube with silencers is shown in Fig. 5.

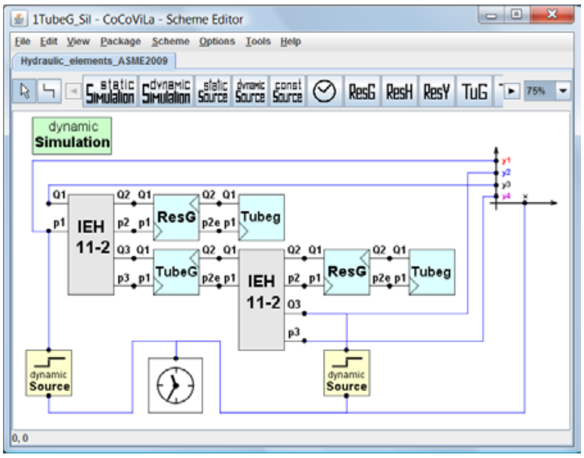

Fig. 5. Simulation task of the transient response of the tube form G with silencers

Tube parameters: l = 14 m, n = 1.

Silencers parameters: for **ResG**: *type* = RRa (round orifice), d = 0.002 m; for **Tubeg**: l = 0.4 m, d = 0.05 m.

Graphs of the transient response of the tube with silencers are shown in **Fig. 6**.

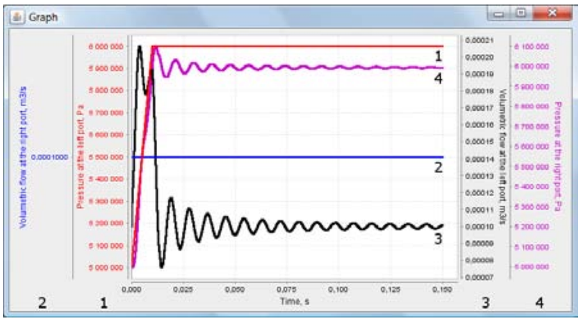

Fig. 6. Graphs of the transient response of the tube with silencers

The processes (3, 4) damp quickly. The remaining vibrations have the frequency $f \approx 115$ Hz. They damp in $t \approx 0.15$ s.

Simulation task of the tube using model TubeY is shown in Fig. 7.

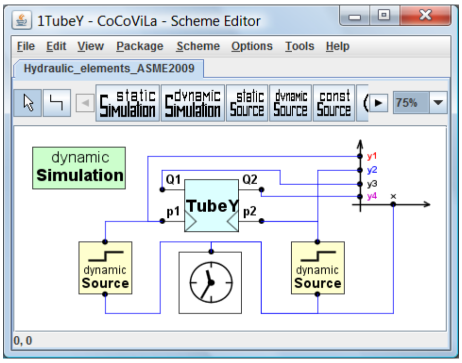

Fig. 7. Simulation task of the tube using model of form Y

Graphs of the transient response of the tube form Y are shown in Fig. 8.

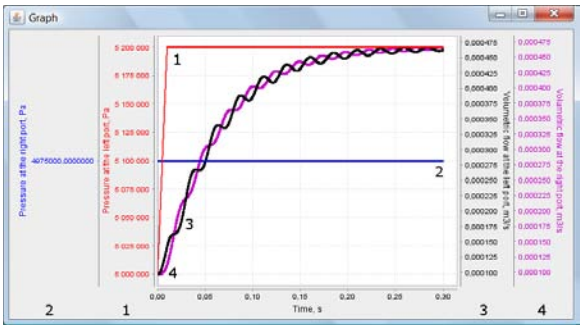

Fig. 8. Graphs of the transient response of the tube of form Y

Disturbance parameters: pressure step disturbance at the left port (1): constant initial value *mean* = 5E6 Pa, step value *step* = 2E5 Pa, disturbance duration t = 1E-3 s; constant pressure at the right port (2): *mean* = 4.975E6 Pa.

The output volumetric flows (3, 4) move to new level in t = 0.3 s with oscillations ($f \approx$ 44 Hz).

Graphs of the transient response of the tube of form Z **are** shown in **Fig. 9**.

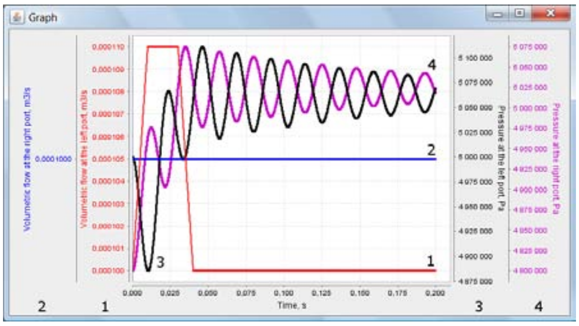

Fig. 9. Graphs of the transient response of the tube of form Z

Disturbance parameters: volumetric flow impulse disturbance at the left port (1): constant initial value *mean* = 1E–4 m^3/s, height of the impulse *height* = 1E-5 m^3/s, disturbance rise and drop durations t = 0.01 s, duration of the impulse *timp* = 0.02 s; constant volumetric flow at the right port (2): *mean* = 1E–4 m^3/s.

The output pressures (3, 4) in opposite phases move to the new level with oscillations ($f \approx 44$ Hz).

For a linear tube model with distributed parameters, without damping, the disturbance propagation velocity is expressed as (Grossschmidt [3]):

$$v = \frac{l}{\sqrt{LC}} \text{ m/s.}$$

In considered examples for tubes with length l = 14 m, using the computed values L = 4.250E7 kg/m^4 and C = 2.794E-12 m^5/N in the beginning of the process, disturbance propagation velocity in the tube v = 1285.75 m/s.

The resonance frequencies of the tube models of forms **G** and **H**, without damping, are expressed

$$f = i\frac{v}{4l} = i\frac{1}{4\sqrt{LC}} \text{ Hz,}$$

where i = 1, 3, 5….

The first resonance frequency calculated by formulae is f = 22.94 Hz, simulated frequency $f \approx 23$ Hz.

The resonance frequencies of the tube models of forms **Y** and **Z**, without damping, are expressed

$$f = k\frac{v}{2l} = k\frac{1}{2\sqrt{LC}} \text{ Hz,}$$

where k = 1, 2, 3….

For this case the calculated first resonance frequency f = 45.88 Hz, simulated frequency $f \approx 44$ Hz.

For tube models of forms **G** and **H,** if quarter lengths of the wave fit with the length of the tube the resonance takes place.

For tube models of forms **Y** and **Z,** if half lengths of the wave fit with the length of the tube the resonance takes place. The first resonance frequency of models of forms **Y** and **Z** is twice higher than the first resonance frequency of models of forms **G** and **H**.

3.2 Transient responses in hydraulic circuits

In the first example, the simulation of transient responses of a hydraulic circuit shown in **Fig. 10** is presented. The circuit consists of tube **TubeG**, hydraulic resistor **ResY** (for example a directional valve), tube **TubeH** and tube **TubeZ** (for example a hydraulic cylinder chamber).

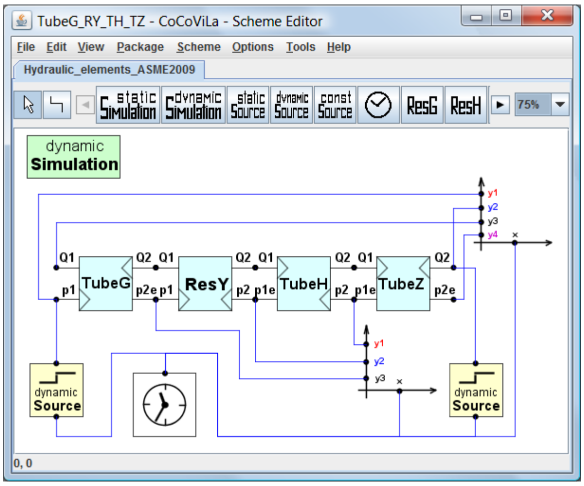

Fig. 10. Simulation task of the hydraulic circuit

Circuit elements parameters: **TubeG:** l = 2 m, d = 0.019 m. **ResY:** *type* = RRd (not round orifice), A = 6E-6 m^2, μ = 0.7. **TubeH:** l = 2 m, d = 0.019 m. **TubeZ:** l = 0.4 m, d = 0.1 m.

Graphs of the transient response of the tube are shown in Fig. 11 and 12.

Disturbance parameters: pressure step disturbance at the left port (1): constant initial value *mean* = 5E6 Pa, step value *step* = 1E6 Pa, disturbance duration t = 0.01 s; constant volumetric flow at the right port (2): *mean* = 1E-4 m^3/s.

In Fig. 11 volumetric flow at the left port (3) first follows the pressure step. Further the volumetric flow with oscillation returns the initial level. Pressure at the right port (4) increases with delay to the new level in time interval t = 0.06 s.

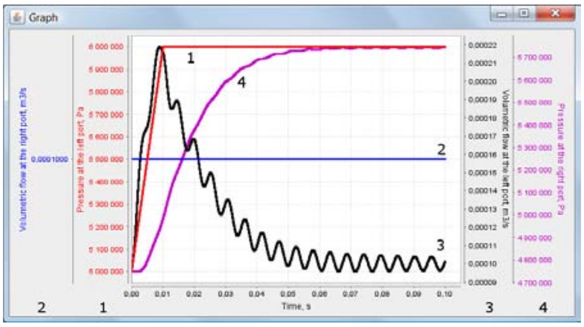

Fig. 11. Graphs of the transient response of the hydraulic circuit

In Fig. 12 pressure (3) at the left port of ResY follows the pressure step disturbance

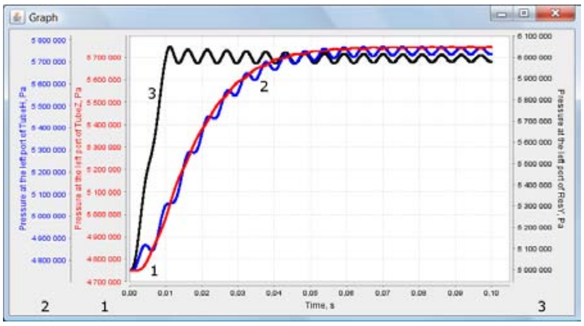

Fig. 12. Graphs of the transient response of the hydraulic circuit

with oscillations. Pressure (2) at the left port of TubeH increases oscillatory to the new level. Pressure (1) at the left port of TubeZ increases to the new level without any oscillations. In Fig. 11 and Fig. 12 all the oscillations damp very slow.

Simulation task of the hydraulic circuit with silencers is shown in Fig. 13.

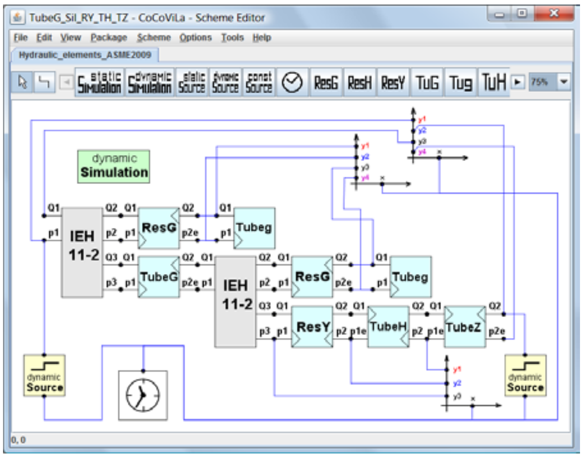

Fig. 13. Simulation task of the hydraulic circuit with silencers

***Circuit element parameters:* TubeG:** *l* = 2 m, *d* = 0.019 m; **ResY:** *type* = RRd (not round orifice), *A* = 6E-6 m^2, μ = 0.7; **TubeH:** *l* = 2 m, *d* = 0.019 m; **TubeZ:** *l* = 0.4 m, *d* = 0.1 m.

***Silencers parameters:* ResG:** *type* = RRa (round orifice), *d* = 0.002 m, μ = 0.7. **Tubeg:** *l* = 0.4 m, *d* = 0.05 m.

Graphs of the transient responses of the circuit are shown in Fig. 14, 15 and 16.

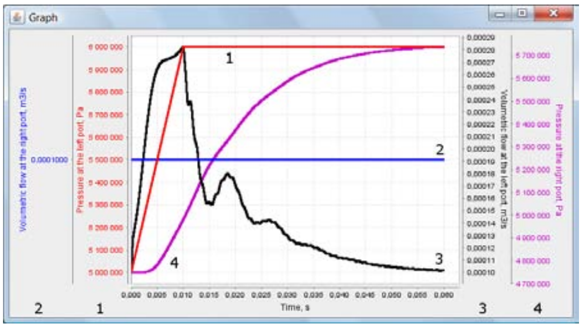

Fig. 14. Graphs of the transient response of the hydraulic circuit with silencers

Disturbance parameters: pressure step disturbance at the left port (1): constant initial value *mean* = 5E6 Pa, step value *step* = 1E6 Pa, disturbance duration *t* = 0.01 s; constant volumetric flow at the right port (2): *mean* = 1E-4 m3/s. If compared Fig. 14 with Fig. 11 (graphs of the same variables of the circuit without silencers) oscillations of volumetric flow at the left port (3) damp faster.

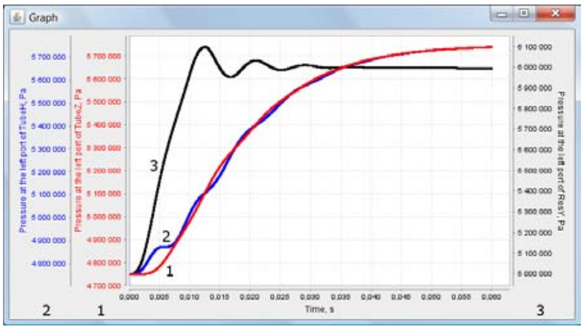

Fig. 15. Graphs of the transient response of the hydraulic circuit with silencers

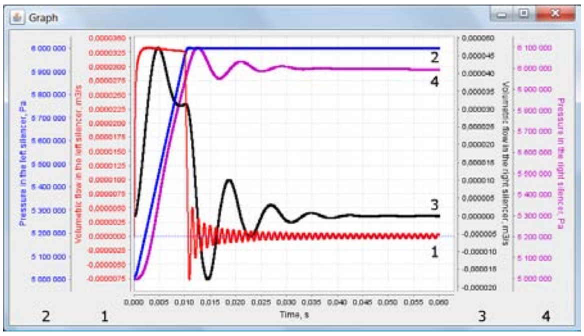

Fig.16. Graphs of the transient response of the hydraulic circuit with silencers

If compared Fig. 15 with Fig. 12 (graphs of the same variables of the circuit without silencers) oscillations damp faster. Oscillations of pressure (4) and volumetric flow (3) in the right silencer damp in time t = 0.04 s. Oscillations of higher frequency $f \approx$ 850 Hz of the volumetric flow (1) in the left silencer take place.

4. USING SIMULATION IN FLUID POWER SYSTEM DESIGN

When designing the fluid power system it is necessary to perform simulations in order to find optimal configuration of the system and parameters values for system components. Simulations must be performed at the first stage of design. The results of initial simulation can be used as a starting point when building trial versions of a real fluid power system. As a result of tests the mathematical models and parameters must be refined. Simulations must be performed once again to prove correctness of used solutions. Finally, the designed system must be experimentally refined and adjusted.

In this way we can achieve a good performance of the designed hydraulic circuit of a fluid power system.

5. CONCLUSIONS

A modelling and simulation system for hydraulic circuits of fluid power systems has been presented.

Multi-pole models of hydraulic elements (tubes, various hydraulic resistors, volume elasticities, hydraulic interface elements) of hydraulic circuits, having various oriented causalities, have been proposed. The relatively simple non-linear four-pole models of the tube dynamics with lumped parameters have been proposed, which enable one to adjust the natural frequency and the damping, in very close agreement with the model with distributed parameters.

All the models have been implemented in the visual programming environment CoCoViLa. Using visual specifications of described multi-pole models one can graphically compose simulation tasks for various hydraulic circuits. The CoCoViLa environment enables one to compose computing programs automatically and perform simulations of steady state conditions and dynamic transient responses of hydraulic circuits.

A couple of simulation examples have been considered.

The proposed tool is suitable for simulation of sophisticated hydraulic circuits of fluid power systems consisting of great number of elements of different types and performing different computations on such models.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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