MULTI-POLE MODELLING AND INTELLIGENT SIMULATION OF A FLUID POWER FEEDING SYSTEM WITH A PNEUMO-HYDRAULIC ACCUMULATOR

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ABSTRACT
An approach based on multi-pole modelling and intelligent simulation is proposed for design of a feeding subsystem with a pneumo-hydraulic accumulator for a fluid power system. Multi-pole mathematical models of feeding system components are presented. Modelling and simulation is explained on the hydraulic feeding system including electric motor, variable displacement axial piston pump, three-directional flow regulating valve and hydraulic accumulator together with hydraulic resistors and check valve. An intelligent visual simulation environment CoCoViLa supporting declarative programming in a high-level language and automatic program synthesis is used as a tool. Simulation examples of dynamics illustrating the behaviour of the accumulator in charging and discharging processes are presented and discussed. Using the proposed models and methods fluid power systems can be designed that are less sensitive to shock effects and high amplitudes of oscillations in the system.

Keywords: fluid power feeding system with a pneumo-hydraulic accumulator, multi-pole model, intelligent programming environment, simulation.

1. INTRODUCTION

To make fluid power feeding systems more flexible it is reasonable to use a hydraulic pump together with hydraulic accumulator. An accumulator enables a hydraulic system to cope with extremes of demand using a less powerful pump, to respond more quickly to a temporary demand, and to reduce shock effects and amplitudes of oscillations in a system.
A hydraulic accumulator is a pressure storage reservoir in which a hydraulic fluid is held under pressure that is applied by an external source. The external source can be a spring, a raised weight, or a compressed gas.
A compressed gas accumulator consists of a cylinder with two chambers that are separated by an elastic diaphragm, a totally enclosed bladder, or a floating piston. One chamber contains hydraulic fluid and is connected to the hydraulic line. The other chamber contains an inert gas under pressure that provides the compressive force on the hydraulic fluid.
In the paper diaphragm and bladder accumulators are considered, the dependences and models concern floating piston accumulators as well.

The stages of working of a bladder hydraulic accumulator are shown in Figure 1.

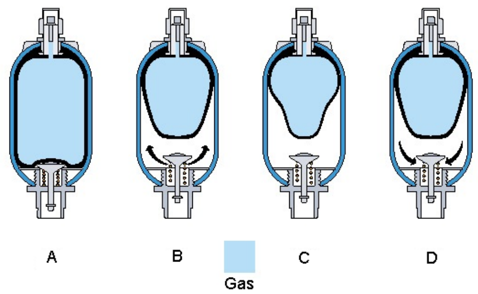

Figure 1: Stages of working of a bladder hydraulic accumulator

Stage A: The accumulator is pre-charged.
Stage B: The hydraulic system is pressurized. As system pressure exceeds gas pre-charge hydraulic pressure fluid flows into the accumulator.
Stage C: System pressure peaks. The accumulator is filled with fluid to its design capacity.
Stage D: System pressure falls. Pre-charge pressure forces fluid from the accumulator into the system.
In (Mamčic and Bogdevičius 2010) review and analysis of hydraulic accumulators and a number of links to scientific works are presented. The paper focuses on pressure pulsations in hydraulic systems, the means reducing them and examines the structure of hydraulic accumulators, including their features and differences.
The analysis of pneumo - hydraulic accumulator efficiency, applied as element of hybrid driving system is presented in (Chrostowski and Kedzia 2004).
Dynamics of accumulators together with hydraulic tubes is analyzed and natural frequencies are calculated in (Murrenhoff 2005).
In (Barnwal, Kumar, Kumar, and Das 2014) effect of hydraulic accumulator on the parameters of a transmission system is considered. The study deals with the surge absorbing characteristics of a hydraulic accumulator and is focused to finding out the suitable size of accumulator which will give less pulsation. The hydraulic system is modelled using MATLAB-SimHydraulics software.
In the current paper an approach is proposed, which is based on using multi-pole models with different oriented causalities (Grossschmidt and Harf 2009, 2014) for describing components of fluid power

systems. In the paper multi-pole modelling of feeding system with a pneumo-hydraulic accumulator is proposed.

2. MULTI-POLE MODELS

In general a multi-pole model represents mathematical relations between several input and output variables (poles). The nearest to physical nature of various technical systems is using multi-pole mathematical models of their components and subsystems.

In hydraulic and mechanical systems variables are usually considered in pairs (effort and flow variable). Multi-pole models enable to express both direct actions and feedbacks.

Each component of the system is represented as a multi-pole model having its own structure including inner variables, outer variables (poles) and relations between variables.

Using multi-pole models allows describe models of required complexity for each component. For example, a component model can enclose nonlinear dependences, inner iterations, logic functions and own integration procedures. Multi-pole models of system components can be connected together using only poles. It is possible directly simulate statics or steady state conditions without using differential equation systems.

The multi-pole model concept enables us to describe mathematical models visually which facilitates the model developing.

3. SIMULATION ENVIRONMENT

CoCoViLa is a flexible Java-based simulation environment that includes both continuous-time and discrete event simulation engines and is intended for applications in a variety of domains (Kotkas, Ojamaa, Grigorenko, Maigre, Harf, and Tyugu 2011). The environment supports visual and model-based software development and uses structural synthesis of programs (Matskin and Tyugu 2001) for translating declarative specifications of simulation problems into executable code.

Designer do not need to deal with programming, he can use the models with prepared calculating codes. It is convenient to describe simulation tasks visually, using prepared images of multi-pole models with their input and output poles.

4. SIMULATION PROCESS ORGANIZATION

Using visual specifications of described multi-pole models of fluid power system components one can graphically compose models of various fluid power systems for simulating statics or steady state conditions and dynamic responses.

When simulating statics or steady state conditions fluid power system behaviour is simulated depending on different values of input variables. Number of calculation points must be specified.

When simulating dynamic behaviour, transient responses in certain points of the fluid power system caused by applied disturbances are calculated. Disturbances are considered as changes of input variables of the fluid power system (pressures, volumetric flows, load forces or moments, control signals, etc.). Time step length and number of steps are to be specified. For integrations in dynamic calculations the fourth-order classical Runge-Kutta method is used in component models.

Static, steady state and dynamic computing processes are organized by corresponding process classes (static Process, dynamic Process). To follow the system behaviour, the concept of state is invoked. State variables are introduced for each component to characterize its behaviour at the current simulation step.

A simulation task requires sequential computing states until some satisfying final state is reached. A final state can be computed from a given initial state if a function exists that calculates the next state from known previous states. This function is to be synthesized automatically by CoCoViLa planner.

A special technique is used for calculating variables in loop dependences that may appear when multi-pole models of components are connected together. One variable in each loop is split and iteratively recomputed to find its value satisfying the loop dependence.

State variables and split variables must be described in component models. When building a particular simulation task model and performing simulations state variables and split variables are used automatically.

5. MULTI-POLE MATHEMATICAL MODELS OF A PNEUMO-HYDRAULIC ACCUMULATOR

5.1. Multi-pole models of pneumo-hydraulic accumulators

A multi-pole model of a pneumo-hydraulic accumulator has input pressure p and output volumetric flow Q (Figure 2a) or input volumetric flow Q and output pressure p (Figure 2b). Additionally the models have the outputs of gas volume V and of temperature T of gas.

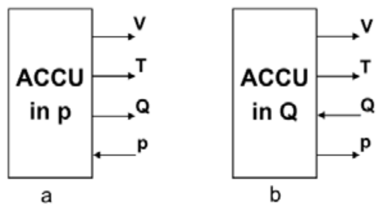

Figure 2: Multi-pole models of a pneumo-hydraulic accumulator

The model (a) is used for calculating static characteristics. The model (b) is used for calculating dynamic transient responses.

The model (a) is more natural also for dynamic. But if the model is directly connected to the resistor with check valve, the iterative calculation process solving the loop dependence during the simulation is not stable. If using model (b) calculations turn out to be stable.

5.2 Mathematical models and characteristics for statics

Here the following notations taken from (Murrenhoff 2005) are used:

p0 - gas pre-charge pressure to accumulator,
p1 - minimum pressure from accumulator,
p2 - maximum pressure from accumulator,
p3 - safety valve pressure,
V0 - maximum gas volume at pressure p0,
V1 - gas volume at minimum pressure p1,
V2 - gas volume at maximum pressure p2,
V3 - gas volume when safety valve turns on at pressure p3.

Gas pre-charge pressure to accumulator is usually taken

$$p0 = 0.9*p1.$$

Gas volume is calculated using formula

$$V = V0 * (p0/p)^{1/k},$$

where
k - polytrope exponent,
k = 1 in case of isothermal process,
k = 1 … 1.4 in case of polytropic process,
k = 1.4 in case of adiabatic process.

Fluid volume in the accumulator is expressed as

$$Vf = V0 – V.$$

Maximum available fluid volume from the accumulator is expressed as

$$Vfmax = V1 – V2.$$

Static characteristic of an accumulator representing dependence of the gas volume on the pressure is shown in Figure 3.

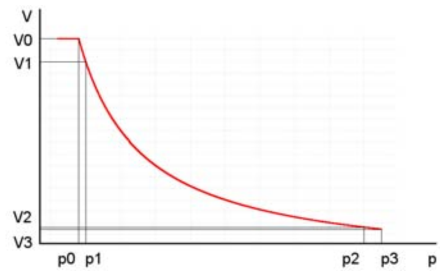

Figure 3: Static dependence of the gas volume against the pressure of in accumulator

This characteristic is calculated as a result of simulation accumulator statics using model from Figure 2a. For pressures p0 = 0.9e6 Pa, p1 = 1e6 Pa, p2 = 5 Pa and p3 = 5.5 Pa the volumes are equal V0 = 1e-3 m^3, V1 = 0.9e-3 m^3, V2 = 0.18e-3 m^3, V3 = 0.164e-3 m^3, Vfmax = 0.72e-3 m^3 at isothermal process.

5.3 Mathematical models for dynamics

For dynamics (accumulator model from Figure 2b) we have an adiabatic process (k = 1.4).
Volume elasticity of the gas

$$CA = dV / dp = – V0 * p0^{1/k} / (k * pold^{1/k + 1}),$$

where
pold – pressure at previous simulation step,
and volume elasticity of the fluid

$$CF = – Vf * \beta m,$$

where

$$Vf = V0 * (1 – (p0/pold)^{1/k}) ,$$

βm – compressibility factor of fluid consisting air.
Sum of gas and fluid elasticities

$$C = CA + CF.$$

In the formulas pressure at previous simulation step pold is used, as the pressure p at current simulation step will be calculated later.
The output pressure is calculated as

$$p = pold + Q * dt / C,$$

where
dt – simulation time step length.
The output gas volume

$$V = V0 * (p0/p)^{1/k} .$$

The output gas temperature (in ºC) is calculated as

$$T = (Told +273.15) * (p/pold)^{(k-1)/k} – 273.15,$$

where
Told – gas temperature at previous simulation step.

6. MULTI-POLE MATHEMATICAL MODELS OF A SIMPLE FLUID POWER FEEDING SYSTEM COMPONENTS

Functional scheme of a simple fluid power feeding system with an accumulator is shown in Figure 4.

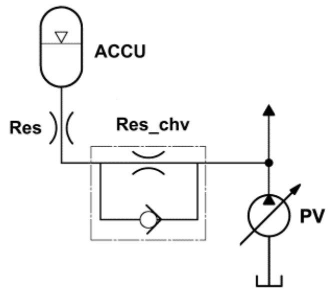

Figure 4: Functional scheme of a simple fluid power feeding system with an accumulator

The simple feeding system with an accumulator includes hydraulic accumulator **ACCU** together with hydraulic resistor **Res** at accumulator inlet, hydraulic resistor with check valve **Res_chv** and a variable displacement axial piston pump **PV**.
The feeding system of proposed configuration is usable for such fluid power systems where pressure at pump depends on load (load sensing systems, etc.).
Oriented graph of the hydraulic feeding system with an accumulator for dynamics is shown in Figure 5.

The oriented graph contains all the hydraulic system components and a hydraulic interface element IEH4. The graphs show all the oriented relations between variables and all the loop dependencies.

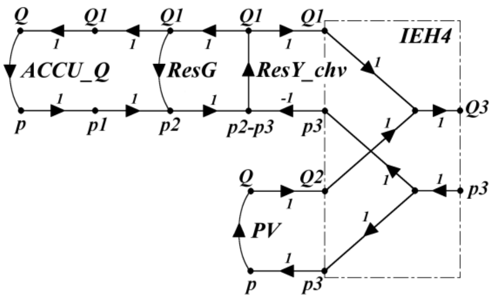

Figure 5: Oriented graph of simple hydraulic feeding system with an accumulator for dynamics

Mathematical model of a hydraulic resistor ResG

$$p2 = p1 - (RL + RT*abs(Q1)) * Q1,$$

where
RL, RT – hydraulic linear and square flow resistances (Grossschmidt and Harf 2010).

Mathematical model of a hydraulic resistor with check valve ResY_chv:

hydraulic resistance of check valve if (p2 <= p3, accumulator charging)

$$R = \Delta p_n / Q_n,$$

where

Δp_n – nominal pressure drop,

Q_n – nominal volumetric flow,

volumetric flow through check valve

$$Q1 = -(p3 - p2) / R,$$

where
p2, p3 – pressure at left and right port,

volumetric flow through hydraulic resistor if (p2 > p3, accumulator discharging)

$$Q1 = \mu * \pi * d^2 / 4 * ((2*(p2 - p3) / \rho)^{½},$$

where
μ – flow coefficient,
d – inner diameter of resistor,
ρ – fluid density.

In interface element IEH4

$$Q3 = Q1 + Q2.$$

Output volumetric flow of variable displacement axial piston pump PV

$$Q = \omega * V * \eta_{vol} \ \ m^3/s,$$

where
ω – angle velocity rad/s,
working volume of the pump

$$V = V_{max} * \tan(al) / \tan(al_{max}) \ \ m^3/rad,$$

where

V_{max} – maximum working volume m^3/rad,
al – position angle of the swash plate rad,

al_{max} – maximum position angle of the swash plate rad,

volumetric efficiency coefficient

$$\eta_{vol} = 1 - k_{vol} * p,$$

where

k_{vol} – coefficient characterizing the dependence from p,

p – inlet pressure.

7. SIMULATION OF DYNAMICS OF FLUID POWER FEEDING SYSTEM WITH AN ACCUMULATOR

7.1. Simulation of simple feeding system

Simulation task of a simple feeding system with a pneumo-hydraulic accumulator for dynamic is shown in Figure 6.

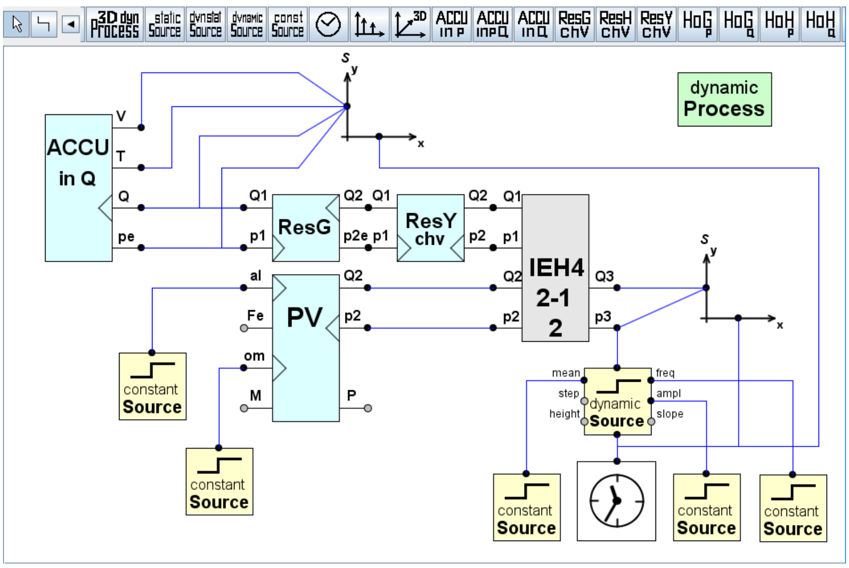

Figure 6: Simulation task of a simple feeding system with a pneumo-hydraulic accumulator for dynamic

In Figure 6 multi-pole models are as follows: accumulator ACCU_inQ, resistor ResG, resistor with check valve ResY_chv, hydraulic interface element IEH4_2-1_2 and variable displacement pump PV (reaction force Fe of the pump swash plate, reaction moment M of the pump and output power P of the pump are not used in the present task).
Dynamic input is denoted as "dynamic Source", constant inputs are denoted as "constant Source". Time is given by "Clock". Simulation process is managed by "dynamic Process". Parameters denoted by suffix "e" (pe in ACCU_inQ and p2e in ResG) are to be computed by using splitting and iterative calculation (see Chapter 4).
In all the examples below the following feeding system parameters are used.

For accumulator ACCU_inQ: p1 = 1e6 Pa, p2 = 5e6 Pa, V0 = 1e-3.

For resistor ResG: d = 0.01 m; for resistor ResY_chv: d = 0.003 m, μ = 0.7, Δp_n = 1e5 Pa, Q_n =2e-4 m^3/s.

For hydraulic pump PV: V_{max} =10.027e-6 m^3/rad, al_{max} = 0.3264 rad, al = 0.23 rad, ω = 154 rad/s, k_{vol} = 2e-9 1/Pa.

The following initial values are used.

For accumulator ACCU_inQ: init pe = 3e6, initV = 2.55e-4 m^3, initT = 40 ºC.

For resistor ResG: initp2e = 3e6 Pa.

For resistor ResY_chv: initQ1 = 0.

For hydraulic pump PV: initQ =10.55e-4 m^3/s.

Physical properties of working fluid (density ρ, kinematic viscosity ν and coefficients of fluid compressibility) are calculated at each simulation step depending on average of input and output pressure in the component. In all the simulations hydraulic fluid HLP46 at temperature 40 ºC is used. Cinematic viscosity at temperature 40 ºC ν = 46E–6 m^2/s, density at temperature 15 ºC ρ_{15} = 875 kg/m^3, volume of air, relative to the entire volume at p = 0, vol_0 = 0.08.
Simulation parameters: time step Δt = 1e-6 s, calculation step 4e5.

Simulated output volumetric flow of the feeding system in case of sinusoidal input pressure is shown in Figure 7.

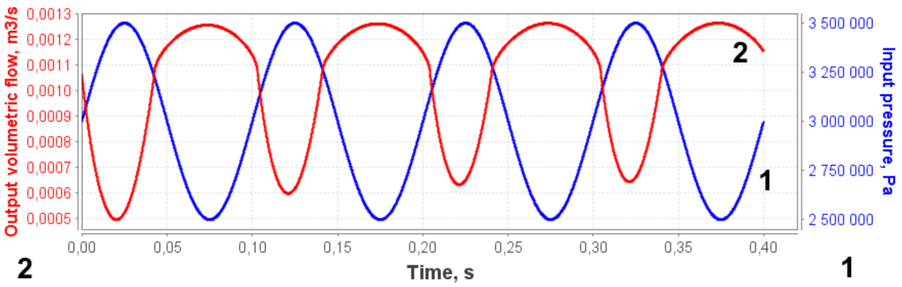

Figure 7: Simulated output volumetric flow of the feeding system and sinusoidal input pressure

The sinusoidal input pressure (graph 1) parameters are: medial value 3e6 Pa, amplitude 5e5 Pa and frequency 10 Hz. The output volumetric flow (graph 2) is as a sum of pump flow and accumulator flow. The accumulator flow accounts the majority of the flow. So the change of output volumetric flow follows mainly the change of accumulator volumetric flow. In case of increasing input pressure the output volumetric flow drops. Charging of the accumulator occurs. Dropping the volumetric flow causes the fluid power system outlet velocity to decrease. In case of decreasing of input pressure the output volumetric flow increases. Discharging of the accumulator occurs with lower amplitude of output volumetric flow. As a result the accumulator works as an absorber of oscillations.
The simulated graphs showing the behaviour of accumulator variables are presented in Figure 8.
Accumulator gas volume (graph 1) is oscillating with phase shift to input pressure. The oscillations are asymmetric, they stabilize during 0.4 s.

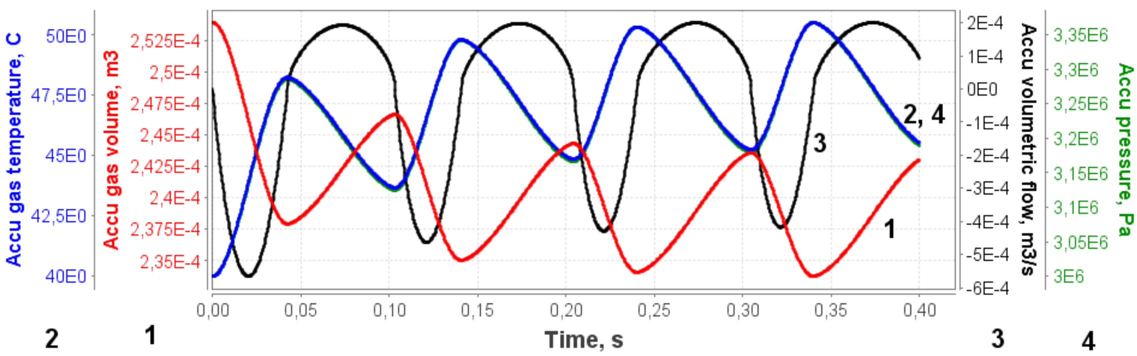

Figure 8: Simulated graphs of accumulator variables in case of sinusoidal input pressure

Graphs of accumulator gas temperature (graph 2) and accumulator pressure (graph 4) overlap. These oscillations are in opposite phase to gas volume oscillations at graph 1.

Oscillations of the accumulator volumetric flow (graph 3) have unsymmetrical amplitudes. At the negative volumetric flow charging and at the positive volumetric flow discharging of the accumulator occurs.

7.2. Simulation of feeding system with three-directional flow control valve

A simulation experiment was performed to demonstrate using an accumulator in a more complex hydraulic system. A hydraulic drive with three-directional flow control valve considered in (Harf and Grossschmidt 2015) was used as basis. A fragment of the drive equipped with an accumulator is shown in Figure 9. The pump **PV** is driven by electric motor **ME** through clutch **CJh**. The outlet of the pump is provided with three-directional flow regulating valve **FRV** and safety valve **SV**. The feeding system is supplemented with hydraulic accumulator **ACCU** together with hydraulic resistor **Res** and hydraulic resistor with check valve **Res_chv**.

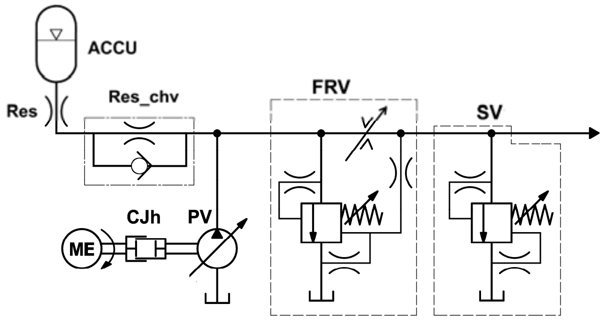

Figure 9: Functional scheme of a fluid power feeding system with an accumulator, three-directional flow control valve and safety valve

In Figure 10 multi-pole models are as follows: electric motor ME, clutch CJh, variable displacement pump PV, accumulator ACCU_inQ with resistor ResG and resistor with check valve ResY_chv, three-directional flow control valve FRV (pressure compensator spool VQAS22, pressure compensator slot RQHC, regulating throttle orifice ResYOrA, resistors ResG_Ch and ResH), safety valve SV (safety valve spool VS and throttle edge of safety valve spool RV) and interface elements IEH.

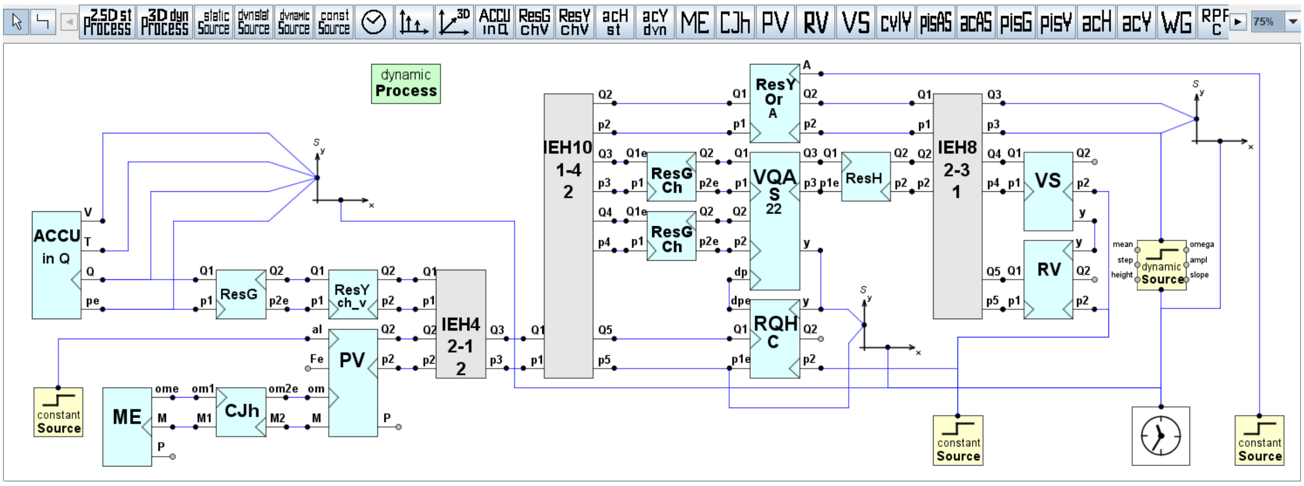

Figure 10: Simulation task of a feeding system with an accumulator

Simulation results are shown in Figures 11 ... 13.

The simulated graphs showing the behaviour of the accumulator are presented in Figure 11.

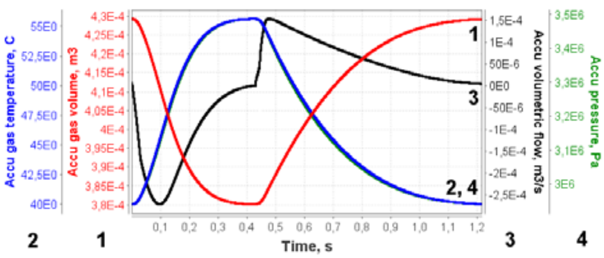

Figure 11: Simulated graphs of accumulator variables in case of impulse input pressure

Accumulator gas volume (graph 1) decreases when the input pressure impulse (graph 1 in Figure 13) stands at maximum. Gas volume starts to increase when the impulse falls and achieves the initial value at 1.2 s. Graphs of accumulator gas temperature (graph 2) and accumulator pressure (graph 4) overlap. When the impulse height is achieved temperature and pressure increase. Temperature and pressure start to decrease when the impulse falls.

Accumulator volumetric flow (graph 3) decreases during the impulse rise. When the impulse height is achieved the output volumetric flow is going to restore the initial level. When the impulse falls, the output volumetric flow increases. After the impulse pressure reaches back to the baseline the output volumetric flow slowly decreases to the initial value at time 1.2 s.

Simulated graphs of three-directional flow control valve FRV are shown in Figure 12.

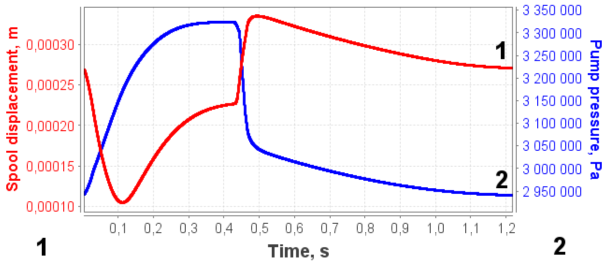

Figure 12: Simulated graphs of three-directional flow control valve

Spool displacement (graph 1) determines pump pressure (graph 2). Pump pressure is applied to accumulator.

Simulated output volumetric flow of the feeding system in case of impulse input pressure is shown in Figure 13.

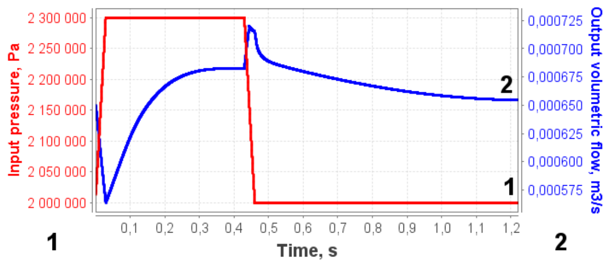

Figure 13: Simulated output volumetric flow of the feeding system in case of impulse input pressure

Impulse input pressure (graph 1) parameters are: impulse rising and falling time 0.03 s, impulse duration 0.4 s, baseline pressure 2e6 Pa and impulse height 3e5 Pa. Feeding system output volumetric flow (graph 2) decreases during the impulse rise. Charging of the accumulator occurs. When the impulse height is achieved the output volumetric flow is going to restore the initial level. When the impulse falls, the output volumetric flow jumps up. After the impulse pressure drops back to the baseline the output volumetric flow slowly decreases to the initial value. Charging of the accumulator occurs rapidly because the check valve of ResY_chv is opened. Discharging of the accumulator occurs slowly because the check valve of ResY_chv is closed.

CONCLUSION

In the paper multi-pole modelling and intelligent simulation of a fluid power feeding system with a three-directional flow control valve and pneumo-hydraulic accumulator has been considered. Mathematical multi-pole models of the system components (accumulator, inlet resistor, resistor with check valve, hydraulic pump) are described.

An intelligent simulation environment CoCoViLa supporting declarative programming in a high-level language and automatic program synthesis is used as a tool for modelling and simulation.

Visual simulation task of a feeding system with a pneumo-hydraulic accumulator for dynamic is presented.

Simulations have been performed and resulting graphs for cases of sinusoidal and impulse disturbances of the input pressure are presented. The graphs demonstrate that using the observable feeding system smoothes volumetric flows to fluid power systems.

Using methodology and simulation system described in the paper enables to perform simulations with accumulators of different parameters. As a result accumulator with optimal parameters can be found for each particular fluid power feeding system.

The feeding subsystem of proposed configuration is usable for fluid power systems where pressure at pump depends on load (systems with three-directional flow regulating valves, load sensing systems, etc.).

ACKNOWLEDGEMENTS

This research was supported by the Estonian Ministry of Research and Education institutional research grant no. IUT33-13, the Innovative Manufacturing Engineering Systems Competence Centre IMECC and Enterprise Estonia (EAS) and European Union Regional Development Fund (project EU48685).

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