Simulation and modeling of a hydraulic system in FluidSim

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Abstract

Modeling and simulation of hydraulic control systems is necessary in order to acknowledge the drawbacks and advantages before even starting a design of a system. By acknowledging, the discrepancies between the model of a physical system and a system in a virtual environment, engineers can handle the optimization, in terms of price and time-consumption. FluidSim is comprenhensive software for simulation of fluid control systems and it is mostly fitted for use in educational purposes. Comparison between the results obtained by mathematical model and FluidSim model of a simple open-circuit hydraulic system results show a low percentage deviation of approximately 3%.

Key words: *hydraulic system, modeling and simulation, fluidsim*

1. INTRODUCTION

Hydraulic systems are used in applications where demand for high power and fast response is required. Such applications include hydraulic industrial mobile machinery, aerospace hydraulics, wind turbines, etc. Simulation and modeling of a hydraulic systems is gaining interest in scientific community [1-4]. Drawbacks in hydraulic systems are seen through

energy dissipation and reliability [5] which sets another problem in hydraulic system design. The mathematical model of a system is compared with the model designed by block diagrams in FESTO FluidSim, which is used to simulate fluid power system behaviour such as hydraulic or pneumatic system. Results obtained from modeling in FluidSim show discrepancies compared to the general mathematical representation of a hydraulic system.
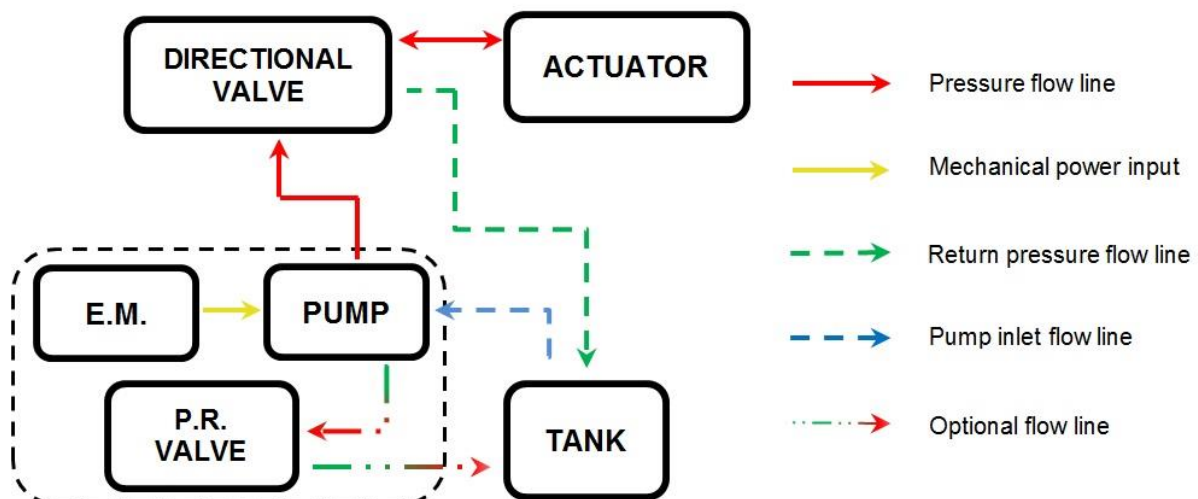

Figure 1. Simplified hydraulic system scheme

2. HYDRAULIC SYSTEM

Hydraulic system used for modeling and simulation is a simple open hydraulic system, which can be used as applications such as: excavator actuation system for a

bucket, hydraulic press, elevator system, etc. The hydraulic system consists of: a reservoir (tank) which provides fluid via suction line to a pump, a fixed-displacement pump driven by an electric motor, a

directional control valve, a hydraulic cylinder, and a pressure-relief valve. Fixed positive displacement pump is used to transform the mechanical energy input from el. motor to pressurizied fluid energy i.e. hydraulic energy. Pressurizied fluid travels through (activated) directional control valve towards hydraulic cylinder. The role of a directional valve is to transfer fluid between the circuits. Usually ports are marked with P, A, B, T (figure 2), and fluid path connections are as follow: P-A and B-T; or P-B and A-T (see figure 2). Port P stands for pressurized port or pump, A and B flow out of directional valve to inlet or outlet of the hydraulic cylinder, while T ports stands for tank i.e. reservoir. Flow from the pump to the pressure-relief valve and to tank is optional:

- in a case of a system overload;

- directional control valve is in middle position (idling);

- fault or failure in a system (e.g. valve jamming – pressure rise activates pressure-relief valve).

2.1 Hydraulic pump model

A fixed positive displacement pump is used in the model of a system. Electric motor is used to drive hydraulic pump. Each pump has its own efficiency, but based on its geometry, design and working pressure, a portion of the flow leaks back to the inlet port. Equation used for pump flow rate is described as follows[6,7]:

$$Q_{PV} = D_P \cdot \omega_P - K_{PS} \cdot p , \qquad (1)$$

and slippage coefficient K_{PS} is described:

$$K_{PS} = \frac{C_S \cdot D_P}{\mu} , \qquad (2)$$

where Q_P is pump flow rate, D_P is the pump displacement, ω_p is the pump angular velocity, p is the pump pressure, C_s is a constant provided by the internal structure of a pump that does not change [8], μ is the absolute viscosity (i.e. dynamic viscosity).

2.2 Directional valve model

Directional valves are designed to direct the flow from the pump to the actuator. There are numerous directional valves in use, such as spool, servo, and proportional valves. Proportional valves impose resistance against the entering flow and thus the flow changes on inlet/outlet. In a conventional hydraulic system if the upstream pressure increases the pressure relief valve opens and bypasses the surpass flow to the tank. Flow from a directional valve is controlled by its orifice area. The flow is calculated as follows [6,7]:

$$Q_{DV} = C_D \cdot A \cdot \sqrt{\frac{2\Delta p}{\rho}} \qquad (3)$$

where C_D is the coefficient discharge (value from [9]), A is the orifice area, Δp is the pressure difference across the orifice, and the ρ is the fluid density. Pressure difference is calculated as follows:

$$\Delta p = \lambda \cdot \frac{L}{d} \cdot \frac{\rho v^2}{2} \qquad (4)$$

where L is the length, d is diameter of the orifice, v is the fluid velocity within a valve, and λ is the friction factor which depends on the Reynolds number (Re):

$$\text{Re} = \frac{v \cdot d}{\upsilon} = \frac{v \cdot d \cdot \rho}{\mu} \qquad (5)$$

where v is the kinematic viscosity, ρ is the fluid density, μ is the dynamic viscosity. Adopting turbulent flow for Re and replacing λ gives by Blasius[10]:

$$\lambda = \frac{0,3164}{\sqrt[4]{\text{Re}}} \qquad (6)$$

2.3. Compressibility

Even though hydraulic fluids are considered incompressible in macro scale [11], they still have small compressibility that needs to be included in modeling of a hydraulic system. However, in this case system is not working at high pressure and flows and it will be neglected. Applications with higher power and high pressure hydraulic machinery, compressibility must be included while modeling the hydraulic system behavior as follows [12]:

$$Q_c = \left(\frac{V}{\beta}\right)\left(\frac{dp}{dt}\right) \qquad (7)$$

replacing:

$$\frac{dp}{dt} = \frac{\beta}{V} \cdot Q_c = \frac{\beta}{V} \cdot (Q_{in} - Q_{out}) \qquad (8)$$

where p is the pressure present at the circuit, β is the bulk modulus, Q_{in} and Q_{out} are the flows entering and exiting the segment, respectively. Equation (7) represents the dynamics of hose or pipe. The compressibility equation must be written for each continuous segment of the circuit because of a pressure discontinuity (pressure rise or drop) caused by a pump, valve or cylinder [11]. In a FluidSim toolbox options for modeling compressibility of a hose or pipe is not known to the authors.

2.4 Hydraulic cylinder model

The function of a hydraulic cylinder is to convert hydraulic energy supplied by the pump into mechanical work at the output. The flow of a ideal hydraulic cylinder is calculated as follows:

$$Q_{cyl} = A \cdot \frac{dx}{dt} \qquad (9)$$

whereas Q_{cyl} is the flow rate, A piston area, and dx/dt velocity (V_{cyl}). With modern sealing technology, the volumetric efficiency (leakage losses) of a hydraulic cylinder in good condition approaches ~100% [13]. While the mechanical-hydraulic efficiency of a cylinder varies with seal type and the tolerances between the piston-rod and its wear bands. A mechanical efficiency of cylinders is calculated as follows [13]:

$$\eta_{mech} = \frac{F}{p_1 A_1 - p_2 A_2} \qquad (10)$$

whereas η_{mech} is the cylinder mechanical efficiency, p_1 and p_2 are the pressure at piston and piston rod area, respectively, while F is the effective piston force. Leakage in the cylinder is necessary to assure seal lubrication, therefore in most cases it does not affect system behavior considerably and is neglected.

2.5 Data used for modeling of a system

Data used for simulation is represented in table 1. Although all data is used for mathematical modeling some of the data is not or can not be included in simulation in a FluidSim.

Table 1. Data used for simulation

Quantity	Symbol	Value	Unit
Pump displacement	D_P	14	cm³/rev
Pump leakage coef.	K_{PS}	20.08	cm³/min*bar
Pump pressure	p	120	bar (10⁵ Pa)
Pump total eff.	η_{uk}	0.85	-
Pump vol. eff.	η_{vol}	0.90	-
Angular velocity	ω_P	1450	rev/min
Fluid density	ρ	844.4	kg/m³
Bulk modulus	β	12665,3	bar
Fluid kin. viscosity	v	15.987	cSt
Flow discharge coefficient	C_d	0.985	-
Orifice direct. valve	d_{dv}	0,008	m
Piston diameter	d_P	0.08	m
Piston rod diameter	d_{PR}	0.03	m

4. FLUIDSIM MODEL

FESTO FluidSim™ software is used for simulation of fluid power system. FluidSim was developed as a joint venture between the University of Paderborn, Festo Didactic GmbH & Co. KG, and Art System Software GmbH, Paderborn. Hydraulic components are explained with textual descriptions, figures, and animations that illustrate underlying working principles [14]. FluidSim model shown in figure 2 consists of a pump unit, directional valve and a cylinder. Data included in modeling of a system is used from table 1.

From the modeling of a system authors found some discrepancies, such as: compressibility in segments from a pump to directional valve and from directional valve to the cylinder, since that are high pressure lines; hydraulic pipelines and hoses can not be modeled; and hydraulic fluid and viscosity type of a hydraulic medium to transfer the hydraulic power is not included. State diagram from the simulation of a represented system is shown in figure 3.
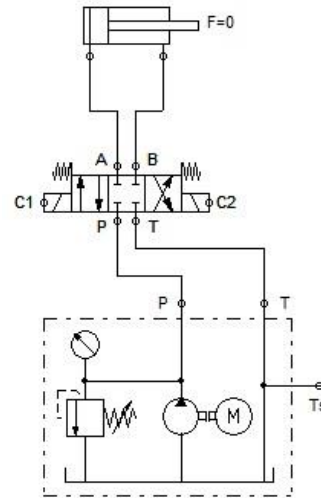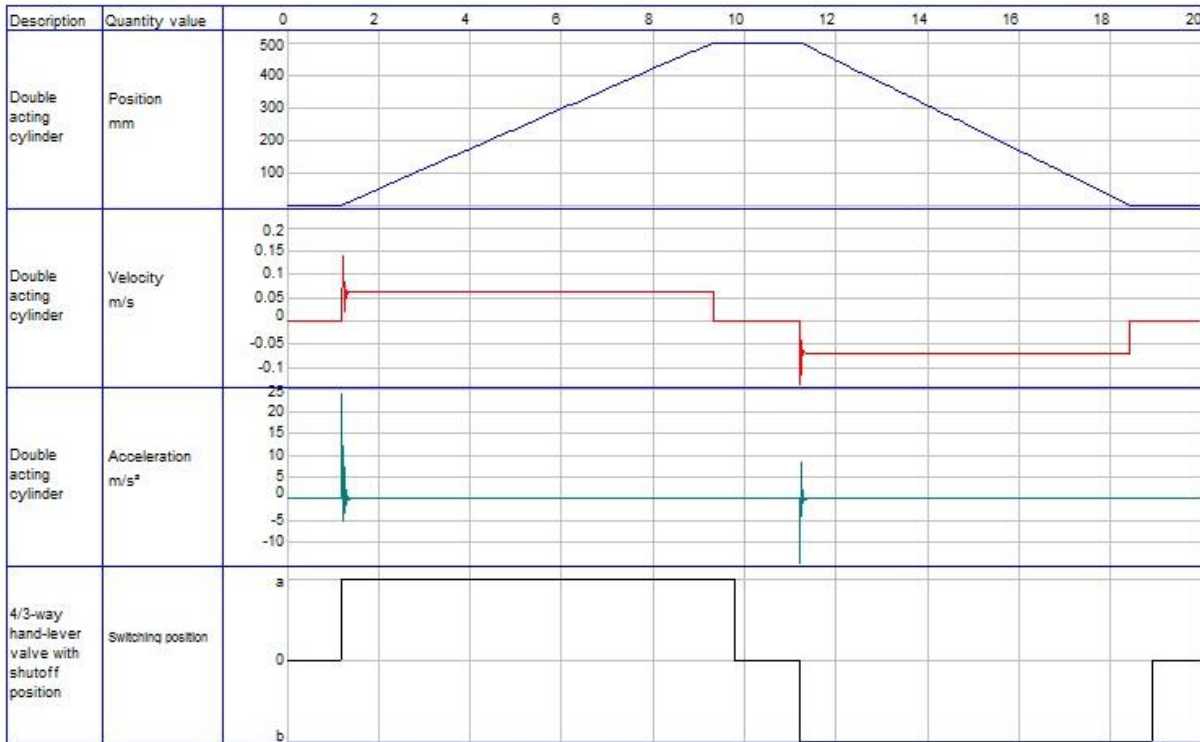

Figure 2. FluidSim hydraulic open circuit system

Figure 3. State diagram of an open circuit hydraulic system in FluidSim

5. RESULTS AND DISCUSSION

The performance of the model is illustrated with a cylinder rod velocity and time for a cylinder to reach the whole range of travel ($s = 0,5m$). Results of a comparison between the mathematical model and FluidSim model shows that extension and retraction of a cylinder in a case of mathematical model consumes $t_{mat}=15,67\ sec$, while simulating in FluidSim consumes $t_{fluidsim}=15,33\ sec$. Results show deviation of a minus ~2,141%. While comparing partially time of cylinder rod extension and retraction results are shown in fig 4-5.
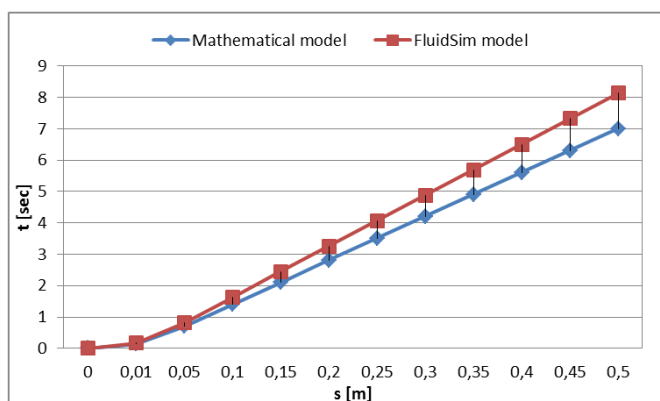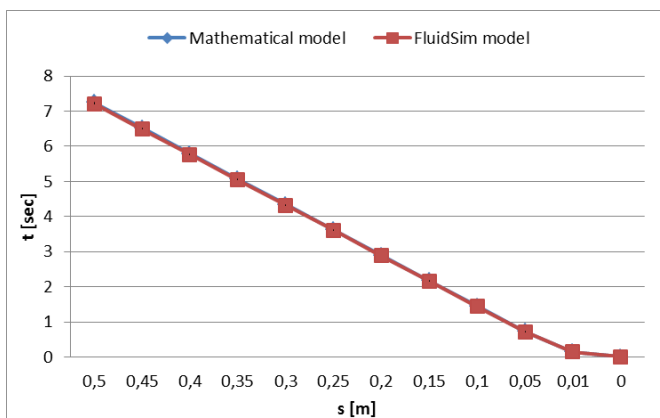

Figure 4. Cylinder extension

Figure 5. Cylinder retraction

While comparing time for cylinder to travel to the back end position, mathematical result show slightly higher time $t_{mat} = 7,24\ sec$ comparing to fluidsim model which took $t_{fluidsim} = 7,204\ sec$, which is ~0,5% deviation. However, results in figure 4 of cylinder extension show a deviation of 3,5% which is much higher ($t_{mat} = 8,429\ sec$; $t_{fluidsim} = 8,133\ sec$).

6. CONCLUSION

Comparing mathematical modeling and modeling via block diagrams in FluidSim results show slight discrepancies. From this particular example of an open-circuit hydraulic system results showed deviation in cylinder movement (extension and retraction time). Authors emphasize that flow out of the pump shows the different results of the flow comparing to mathematical simulation. Besides, authors also emphasize that options for setting the values within the hydraulic directional valve (coefficient of discharge C_D, orifice diameter d) other than hydraulic resistance does not exist.

FluidSim has some disadvantages, although in cases where fast response rate and precision can be somewhat neglected, results can be within allowable range. However, modeling some of the components there are limited access to manually setting component characteristics.

Advantages of using FluidSim toolbox for simulation of the system is seen through easy access modeling and user-friendly options. While performing the simulation of the system software allows dynamic movement of the hydraulic system components (e.g. cylinder extension and retraction) while performing the simulation itself.

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