Fluid-Structure Interaction Simulation of Flow Control Valve

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Abstract. Flow control valves are commonly used in fluid power systems. Controlled by proportional solenoid allows to control flow rate irrespective of pressure on inlet or outlet of the valve. Simulation of such valve is complex task due to the usage of throttle and compensating valves inside one housing. This work presents an attempt of using CFD simulation with implemented Fluid Structure Interaction for simulation of flow control valve under changeable working conditions.

Introduction

Flow control valves which main function is maintaining constant flow rate during system operation irrespective of possible pressure changes are commonly used in fluid power systems. Constant flow rate is achieved by combining hydraulic components (valves) with proportional controllers. Presented in this work flow control valve consists of throttle valve adjusted by electronically controlled solenoid and compensation valve. Regardless of using proportional control system research on ensuring adequate quality and reliability of such valves is required. Quality of control depends on knowledge of phenomena which occurs inside valve during fluid flow. The key issue are flow forces generated on valve components. Research on them are conducted for decades and theirs origin has been explained by Lee and Blackburn [1]. Presented theory based on momentum conservation theory and defines flow forces as a function of flow rate and valve opening. However, this not allows to describe flow forces with acceptable quality today. New possibilities brought numerical methods in flow simulations (CFD) [2]. From the early beginning such tools have found application in modelling flow inside valves and particularly calculation of flow forces. Borghi at al. [3] have investigated flow forces and jet angles in spool control valve. Lisowski at al. [4] have made an experimental tests and simulations for solenoid operated control valve. Along with CFD simulations Lugowski [5] have conducted experimental research on pressure distribution inside spool valves. Despite huge achievements in simulation tools recent research have been conducted on fixed position of valves components, while valve components (spools or poppets) depends directly on flow conditions and in consequences on forces values. Latest implementation of possibilities in simulation of fluid and structure interaction into CFD tools opens new era in simulation of hydraulic valves.

This works is an attempt of implementation of Fluid-Structure Interaction (FSI) for flow control valve. Numerical simulations have been conducted with general purpose CFD code:

ANSYS CFX. Created model of flow control valve has been tested for variable flow conditions, which may appear during normal operation.

The experience gained during the simulation and the developed guidelines will be useful for analogous thermomechanical calculations of flows in biotechnological equipment [6, 7], impact modelling of steel [8], pressing and sintering powders [9] and laser treatment of ESD coatings [10-12]. They can also have a significant impact on the practical use of the thermodynamic adjustment calculus [13] and estimation of the uncertainty of the obtained results [14, 15]. Some optimization techniques may also be useful in general optimization problems [16-18].

Flow control valve

Flow control valve presented in Fig.1 is solenoid controlled proportional vale which consists of throttle valve with spool (3) and compensation valve with spool (2). Required flow rate is maintained by setting position of throttle valve (2) by the usage of solenoid. When pressure on port A (inlet) or port B (outlet) changes than required flow rate is adjusted by proper position of compensation valve with spool (2).

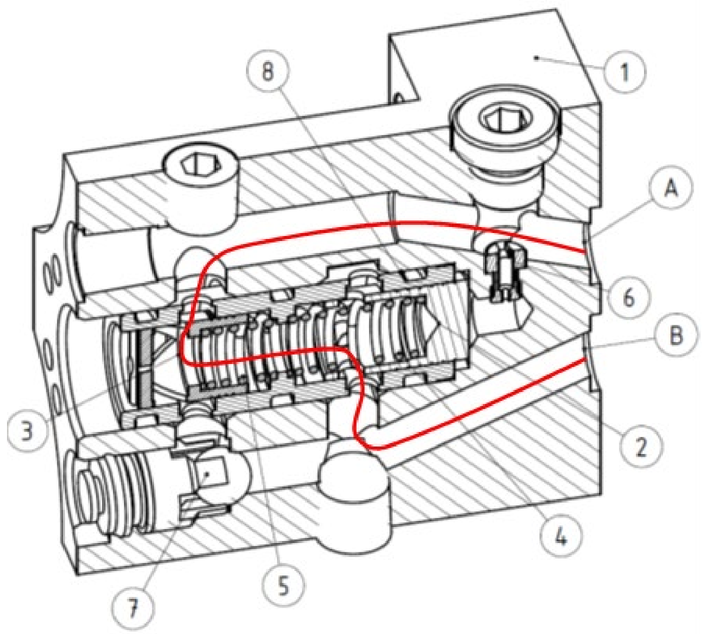

Fig. 1. Flow control valve: 1-valve body, 2,3-spools, 4,5-springs, 6-nozzle, 7-non return valve, red line indicates flow direction (from port A to port B), 8 sleeve.

Both spools (2,3) are inserted into sleeve (8) with springs which make common chamber for both valves. Working fluid from supply line flows into the vale through port A and through throttle spool (3) to common chamber and flowing out through spool (2) to port B. During fluid flow position of spool (2) depends on pressure on both ports A and B. As position of spool (3) is controlled by solenoid, position of spool (2) is determined by forces caused by fluid flow and spring (4). Proper design of this spool is crucial for obtaining adequate quality control of flow rate while value of hydrodynamic forces generated on spool (2) plays major role.

According to force balance (Fig.2), the motion equation for spool (2) can be expressed as:

$$m_e \ddot{x} = F_{hs1} - F_{hs2} - F_s - F_{hd} - F_t \tag{1}$$

$$F_{hs1} = p_1 A \quad (2)$$

$$F_{hs2} = p_2 A \quad (3)$$

$$F_s = F_0 + kx \quad (4)$$

$$F_t = \mu\pi dl \frac{\dot{x}}{c_r\sqrt{\left(1-\left(\frac{e}{c_r}\right)^2\right)}} \quad (5)$$

$$F_{hd} = \rho Q v \cos(\alpha) \quad (6)$$

where:
m_e – effective moving mass (spool, spring and moving fluid), F_{hs1}, F_{hs2} – hydrostatic forces, F_s – spring force, F_{hd} – hydrodynamic force, F_t – friction force, p_1, p_2 – pressure, A – spool area, μ – fluid viscosity, c_r – radial clearance, e – eccentricity, l – spool length, d – spool diameter,
k – spring rate, ρ – fluid density, Q – fluid flow rate, α – jest angle.

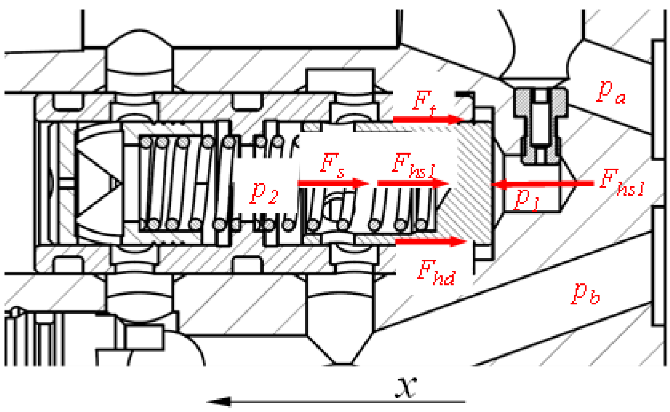

Fig. 2. Force balance on spool 2.

The last two terms of Eq. (1) seems to be the most problematic. As the friction forces might be neglected for steady state conditions the hydrodynamic forces are still the issue. Due to that CFD tools have to be used, in which flow forces are calculated as an integral of stress tensor over surface:

$$F_{hd} = \int \tau_n \mathrm{n} dS \quad (7)$$

where:
τ_n – stress tensor, n – normal vector.

CFD simulation
CFD simulations have been performed in two stages. First the full model of the valve have been used. It has confirmed that velocity distribution in both throttle and compensating value is not uniform in all valves holes. Selected results of path lines colored by fluid velocity have been presented on Fig. 3.

Most of research have estimated forces for fixed position of valve components. Lisowski and Filo [4] have evaluated jet angles in CFD simulations and they have implemented them in Simulink model. Other approach was using deforming mesh and FSI simulation. Beune et al. [19] have used mesh deformation to simulate high pressure safety valve in 2D model. Menendez-Blanco et al. [20] have used 2D and 3D model with various techniques of mesh deformation to simulate diaphragm pump and check valves.

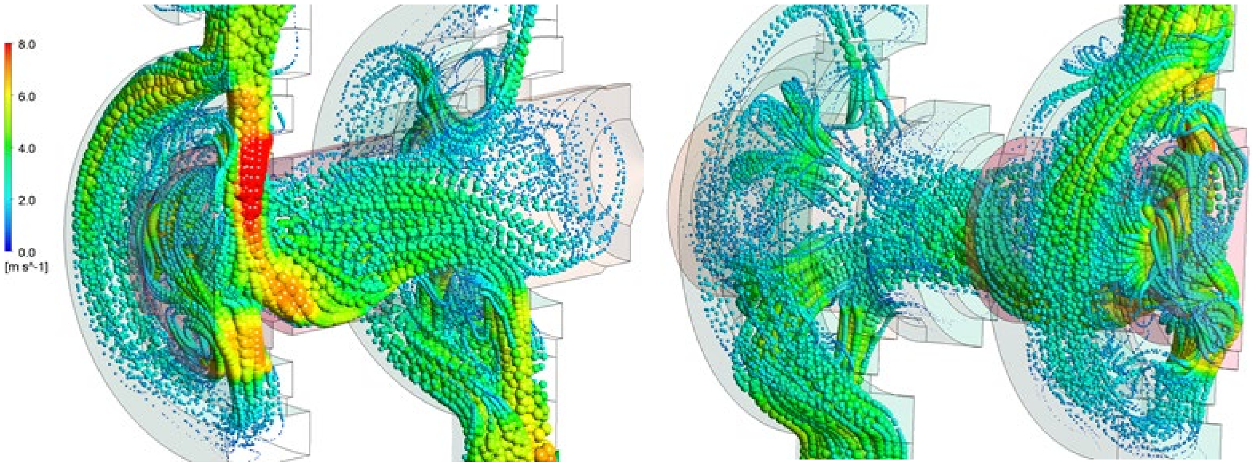

Fig. 3. Path lines colored by fluid velocity.

There are few approaches of performing FSI simulation and enabling motion of rigid bodies. Grid may be stretched and expanded, but as previous works [21-23] have shown problems may happen with distorted cells. Others methods like layering, sliding mesh or overset mesh [24, 25] are also available. After analysis of deforming mesh capabilities a sliding mesh has been used. CFD model of flow control valve has been split into two parts. Model of compensating valve has been used in FSI simulations, remaining part of the model has been used to define input data for FSI simulations. The way the model has been split is presented on Fig. 4.

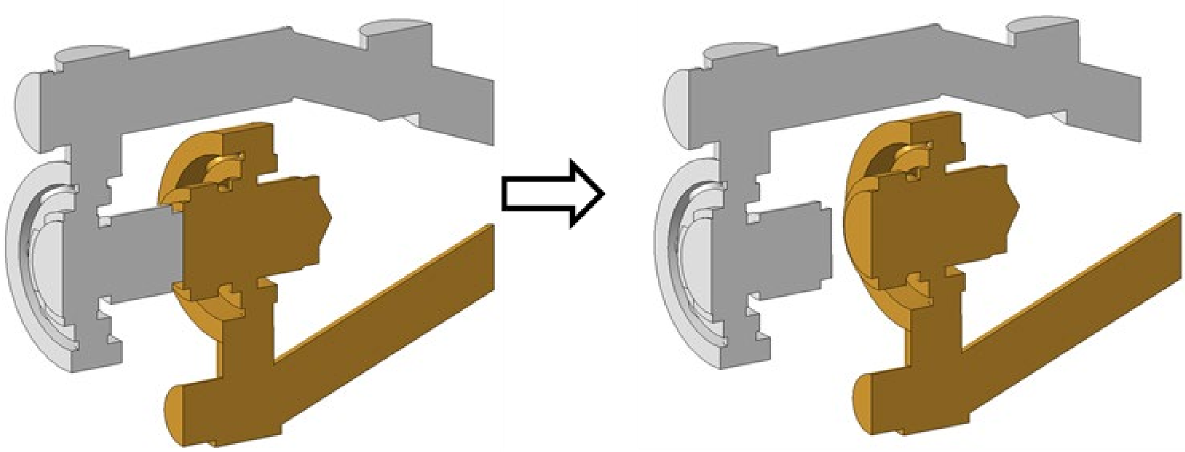

Fig. 4. Splitting of CFD model.

Grid between spool chamber and sleeve have been connected by interface which allows for mass transfer between domains. Grid interface is presented on Fig. 5.

Interaction between flowing fluid and model of spool (2) has been enabled by applying Eq. (1) to spool model by using Newmark scheme [9], which is trapezoid rules with second order accurate scheme:

$$x_{n+1} = x_n + \Delta t \dot{x}_n + \frac{\Delta t^2}{4}(\ddot{x}_n + \ddot{x}_{n+1}) \tag{8}$$

where: index "*n*" is a step number and Δt is time step, x – spool displacement.

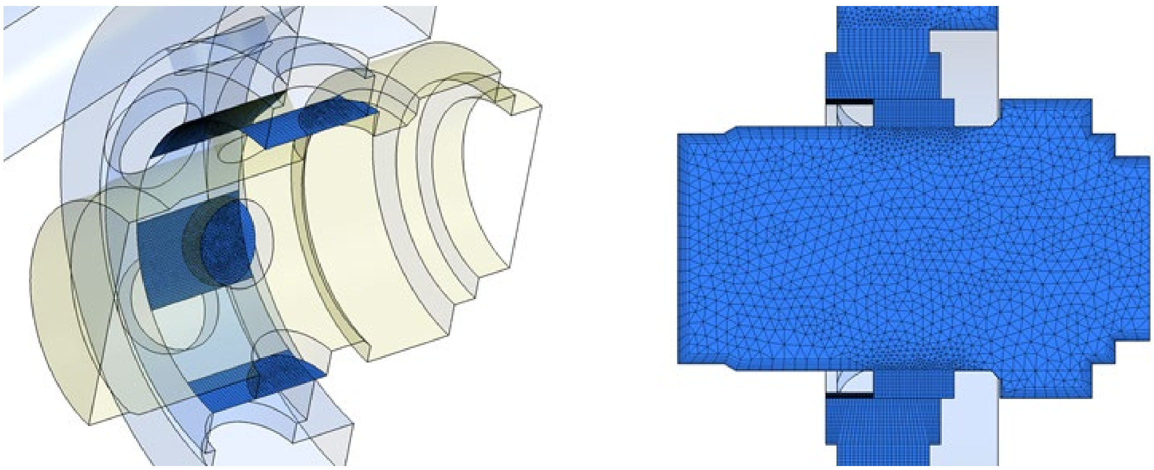

Fig. 5. Grid interface.

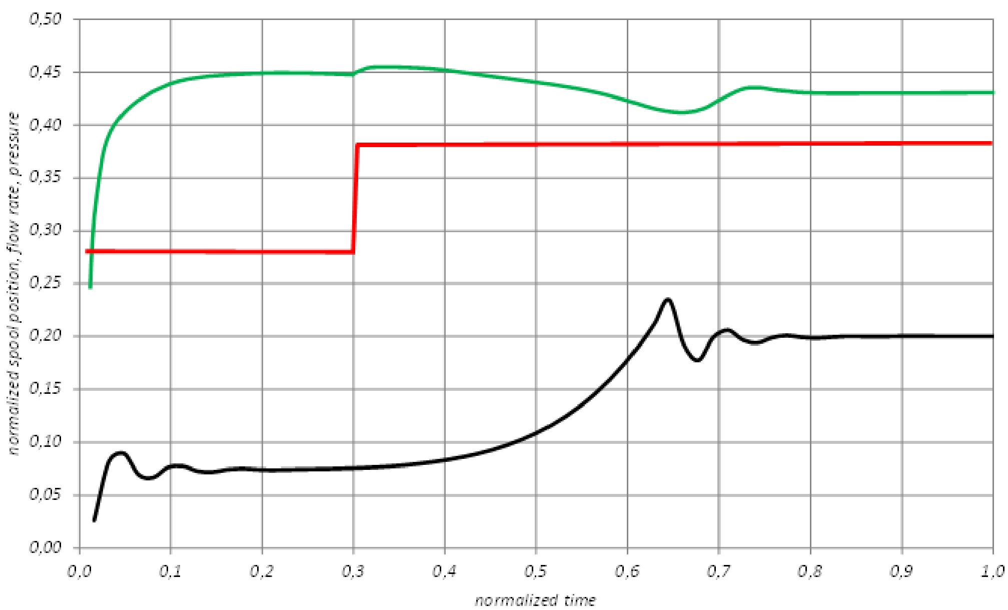

Fig. 6. Spool displacement: black, pressure at outlet: red, flow rate: green.

Numerical simulations have been conducted for case when pressure on outlet has changed from initial value to new value with a step function. At the first stage (to 0.2 of normalized time) spool is oscillating. After achieving steady position pressure on outlet have increased (at value of 0.3 of normalized time). Spool has been moved making flow gap smaller to maintain constant flow rate. Spool displacement and pressure on valve outlet and flow rate value are presented on Fig. 6 as a normalized values.

Conclusions

CFD FSI simulation have been used to simulate operation of flow control valve. A sliding mesh with grid interface has been used to for interaction between flowing fluid and spool of compensating valve. Numerical simulation for case study have been performed in Ansys CFX a general purpose CFD code. Thanks to created model and direct implementation of motion equation for spool it was possible to simulate response of the spool for changes of outlet pressure. Presented in the work approach seems to be an effective method of investigating dynamic phenomena which occurs during fluid flow in hydraulic valves. It is more time consuming process than simulations with fixed spool position but brings new quality in modeling of valve dynamics.

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