

Numerical Study on the Dynamics of Hydraulic Systems Controlled by Proportional Valves

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Abstract: *In order to ensure efficiency in modern hydraulic actuation this study presents a numerical hydraulic actuation system analysis, using the numerical analysis method for modelling and simulation. The study aims to develop a rigorous mathematical model that describes the dynamic behaviour of the hydraulic components, represented by proportional valves and hydraulic cylinders. Based on this model, nonlinear differential equations are formulated that characterize the evolution of pressure, flow rate and actuator displacement velocity. While the numerical simulations can be performed for different operating conditions, including the variation of constructive parameters and control signals, the obtained results allow highlighting the influence of hydraulic parameters on the stability and performance of the system, as well as validating the efficiency of the numerical method used. The paper demonstrates that the numerical analysis environment represents an accessible and efficient for the theoretical analysis of hydraulic systems, providing a solid basis for their design and optimization.*

Keywords: *Hydraulic actuation, fluid flow parameters, modern techniques, numerical analysis*

1. Introduction

In the context of the accelerated development of control technologies and the need for energy optimization, the analysis of the dynamic behaviour of hydraulic systems has become essential. The study of hydrodynamic phenomena, pressure and flow variations, as well as the interaction between mechanical and hydraulic components allows the design of more efficient, more stable and easier to control systems. At the same time, the complexity of internal processes — such as fluid compressibility, pressure losses, valve nonlinearities and actuator dynamics — requires the use of advanced modelling and simulation methods.

Numerical simulation is today an indispensable tool in the analysis of hydraulic drives, as it allows the investigation of the system behaviour without the need of expensive physical prototypes or laborious experiments. The numerical analysis platforms, due to accessibility, syntax and numerical integration tools, provide an efficient environment for developing mathematical models and performing precision simulations. Through it, multiple operating scenarios, parametric optimizations and control strategies can be quickly analyzed.

The present work aims to develop a rigorous numerical model for a hydraulic drive system and to investigate its behaviour under various operating conditions. Both the theoretical foundations of the modelling and the numerical implementation are presented, along with the interpretation of the obtained results. Thus, the work provides a solid foundation for understanding and optimizing modern hydraulic systems.

Hydraulic drive systems are essential technical solutions in many industrial fields due to their ability to transmit and control large forces with high precision. This type of system uses an incompressible fluid to transfer energy from the power source to an execution element, ensuring stable and predictable linear or rotary movements. Due to their high energy density, flexibility in configuration and operational reliability, hydraulic drives are frequently found in mobile equipment, construction machinery, automated industrial systems, as well as in lifting, pressing or positioning applications. In addition, the robustness of the components and the ability to operate in difficult conditions make hydraulic systems a preferred option where performance and safety are a priority 0, 0, 0.

2. The hydraulic system model

A model of a hydraulic system for driving a linear motor with a return spring powered by a proportional valve from a pressure source and volumetric flow of hydraulic agent is proposed for analysis, while a fluid reservoir is connected to the discharge branch. This construction represents one of the simplest linear motor drive schemes that can achieve an axial translation of a mass or an equipment working body.

The hydraulic system is modelled by an assembly of interconnected mechanical and hydraulic elements represented by the hydraulic spring rod cylinder or linear actuator motor with elastic return, being powered by a 4/3 proportional distributor for which the specific equations to be considered within the numerical model will be written 0, 0, 0.

Considering the mechanical dynamics of the piston the equations of motion are:

$$m \frac{d^2x}{dt^2} = A \cdot p - k \cdot x - F_f \quad (1)$$

$$F_f = b \cdot v + F_c \tanh\left(\frac{v}{\varepsilon}\right)$$

where:

m – piston mass;

A – piston surface;

p – pressure in the supply chamber;

k – spring constant;

F_f – friction force;

b - coefficient of viscous friction;

F_c - Coulomb force.

When the system starts operating, the equations describing the dynamics of the hydraulic pressure must be considered, because the pressure value in the cylinder evolves according to:

$$\frac{dp}{dt} = \frac{\beta}{V} (Q - Av) \quad (2)$$

where:

β – bulk modulus of the working fluid;

V – chamber volume depending on the piston position;

Q – valve flow rate;

Av – volumetric flow rate due to piston displacement.

The 4/3 proportional valve model can be introduced into the calculation through the fluid flow rate corresponding to the connection that supplies the cylinder chamber and for the main sequences corresponding to the valve, for both the supply and the discharge of the working fluid on the admission/return branches which are modelled as follows:

I. Supply (positive opening):

$$Q_a = K_v u \sqrt{\frac{2(p_s - p)}{\rho}} \quad (3)$$

II. Discharge (negative opening):

$$Q_e = -K_v |u| \sqrt{\frac{2(p - p_b)}{\rho}} \quad (4)$$

where:

K_v - valve flow coefficient;

p_s – source pressure or hydraulic system supply pressure;

p_b – back-up pressure.

The proportional valve control is achieved through a control function $u(t)$ which is defined as a step signal between 0.1 and 0.8 s which allows the analysis of the system response to a transient command.

The numerical simulation is performed by solving the system of ordinary differential equations (ODE) which is solved by means of a Runge-Kutta solver with adaptive step, suitable for moderately rigid systems, while in the initial conditions the piston is declared at the retracted position and the pressure is equal to the back-pressure 0, 0.

Numerical results are expected for the piston position, indicating the increase in position value and the movement of the piston in the cylinder due to the pressure generated by the valve.

The maximum position is provided which coincides with the piston stop to prevent the mechanical stroke from being exceeded.

Also, with reference to the piston speed, the transient response of the system and the effect of friction must be shown as well as the increase in pressure in the cylinder reflecting the fluid supply through the valve. The back-pressure limitation prevents the pressure from falling below the physical minimum value.

It should be highlighted that the model includes important nonlinearities related to Coulomb friction forces, back-pressure limitation, as well as fluid flow proportional to the square root of the pressure difference, and this approach allows a realistic simulation of the response of a hydraulic cylinder actuated by a 4/3 proportional valve 0, 0, 0.

The model is scalable, meaning that it can be extended with temperature models, temperature-dependent viscosity, or valves with neutral zones.

3. Numerical analysis for hydraulic fluid flow

Based on the above nonlinear dynamic model for the hydraulic actuation system a numerical analysis is developed in order to investigate the interaction between hydraulic pressure dynamics and mechanical translational motion parameters of the cylinder piston.

The system is described using a lumped-parameter approach, considering fluid compressibility, variable chamber volumes and piston dynamics.

The adopted model has the ability to simulate the position, velocity and pressure in the cylinder for the axial movement of the spring-loaded hydraulic piston and includes the nonlinearity of the circulated fluid flow through the directional valve.

The proposed framework provides a flexible and computationally efficient basis for parametric analysis and control-oriented study of hydraulic actuation systems 0, 0, 0, 0.

The results of the numerical analysis are presented in terms of position, velocity and pressure of the cylinder piston, and are shown in Figure 1.

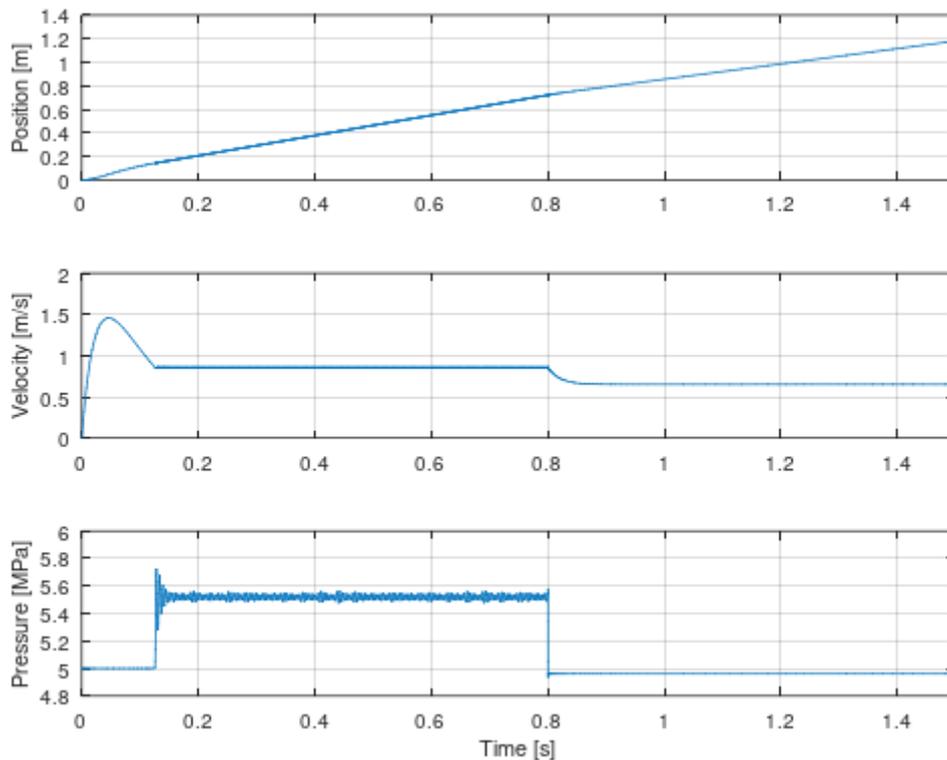


Fig. 1. The obtained results from numerical analysis

The simulation of the hydraulic cylinder was performed for the time interval $t=[0, 1.5]$ s with the initial conditions presenting the situation in which the piston is at the initial position $x_0=0$ m, the initial velocity $v_0=0$ m/s and the pressure equal to the back-pressure $p_0=p_b$, the valve control was performed by means of a step signal of amplitude 0.6 in the range of 0.1-0.8 s and the graph for the piston position $x(t)$ shows the rapid increase immediately after the valve opens at $t=0.1$ s.

The position increases approximately linearly during the acceleration phase, then stabilizes as the piston approaches the end of its maximum stroke $x_{max}=0.15$ m, while this curve reflects the balance between the hydraulic force generated by the pressure and the mechanical resistance forces (spring + friction).

The velocity $v(t)$ exhibits a transient response characteristic of mechanical systems with mass and damping. Initially, the piston accelerates rapidly due to the increasing pressure, reaching a maximum level, while later the velocity decreases when the friction and spring pressure forces become comparable to the actuating force.

Observation of this curvature allows the estimation of the system response time and the effect of friction on the dynamic performance.

The pressure $p(t)$ increases with the opening of the valve, reaching a maximum during the active phase of the control signal and after the valve closing, the pressure gradually decreases to the back-pressure value, being emphasized the pressure limitation below the visible pressure limit, confirming the protection implementation: $dp/dt=0$ for $p \leq p_b$. This limitation prevents the simulation of physically impossible states and reflects the real behavior of the hydraulic system.

The position and velocity graph provides information about the mechanical response, including acceleration and the friction effect, while the pressure graph allows the performance of the 4/3 proportional valve to be evaluated and back-pressure constraints to be verified.

These results are fundamental for the design and control of hydraulic systems and can be used in the optimization of valve parameters, piston mass or friction coefficients.

4. Conclusions

A numerical model of a hydraulic actuator system was developed in this work that can be

implemented to correctly describe the mechanical and hydraulic dynamics of a cylinder with a 4/3 proportional valve, including the effects of Coulomb friction forces, viscous friction and pressure limits.

The importance of pressure protection is shown by the possibility of ensuring the pressure values limitation within safe limits, thus ensuring the numerical stability conditions for the simulation and thus functionality which is essential for the realistic simulation of hydraulic systems.

The characteristics of the proportional valve were highlighted in the model through the valve flow rate coefficient and the supply pressure that determine the piston response velocity and the maximum reached pressure level.

The practical utility of the model allows the analysis of the transient response of the cylinder to specific commands, the evaluation of maximum to minimum velocities and pressure level which can be used for optimizing the system parameters or designing hydraulic control.

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