Implementation of Piezoelectric Actuators for Pilot Valve of High Response Hydraulic Servo Valve

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Abstract. The high degree of automation in the use of electronic control in all industrial and mobile applications is most often done by hydraulic proportional control devices, where the regulating element changes remotely in proportion to the electrical signal. This provides the possibility to change the parameters of the hydraulic energy – flow rate and pressure – a realization of adaptive control by proportional electric control. The focus of this study is set on piezoelectric actuators that are electromechanical transducers, suitable for driving and controlling high-speed hydraulic actuators and relatively small insensitive zones. Detailed analysis of various existing designs is performed prior to development of conceptual model. Further, a design exploration is performed through virtual prototypes that helps studying in high level of detail various work parameters. It is of great importance for successive design development as some of the controlled parameters (as deformations) are very sensitive and has great influence over device performance.

Keywords: Hydraulics · Pilot valve · Piezoelectric · Virtual prototyping

1 Introduction

Hydraulic proportional control valves are devices in which the position of the regulating element changes remotely in proportion to the electrical signal. This provides the possibility to change the parameters of the hydraulic energy – flow rate and pressure, during the production process and realization of adaptive control of the machine itself. The most widely used application is the hydraulic valves with proportional electric control, that are divided into two main types: proportional valves and servo valves. Servo valves differ from conventional proportional valves with higher performance and overlapping close to zero. They have better static and dynamic characteristics than proportional valves and they are mainly used in electrohydraulic closed-loop systems to control the speed and position of hydraulic machines (hydro cylinders and hydro motors). The main directions of design improvements are oriented towards their dynamic behavior, reduction of hydraulic losses, improved performance and providing other advantages (egg. low cost) over conventional directional control valves and

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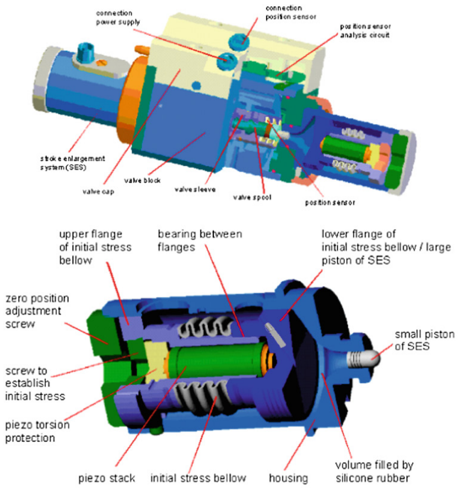
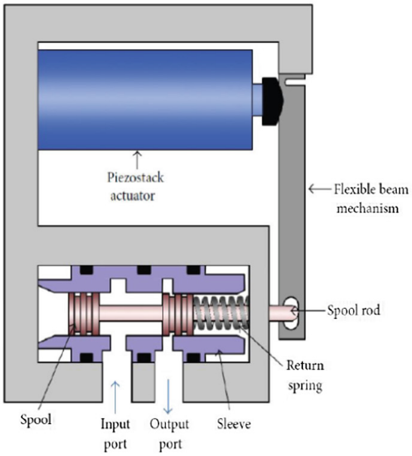
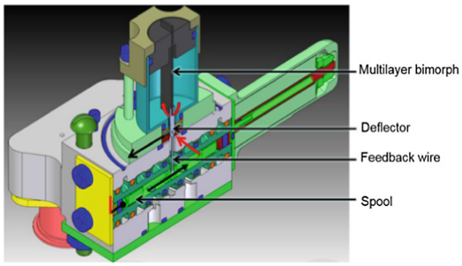
conventional pilot operated valves. Recently, the development of hydraulic valves is directed to novel methods for actuate the regulating element (the most common of spool type). Modern technical solutions in this area are using stability piezoelectric transducers built into the hydraulic control devices for industrial and mobile applications [1–3] (Fig. 1).



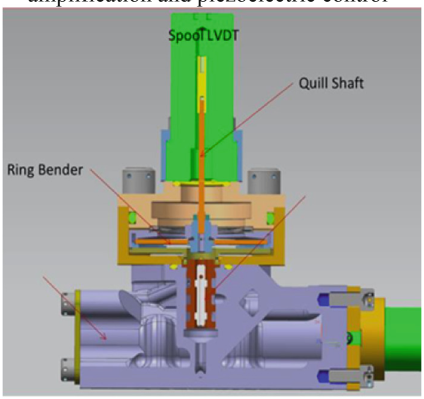
A/ Proportional valve with hydrostatic amplification and piezoelectric control



B/ Proportional valve with mechanical amplification and piezoelectric control



C/ Servo valve with hydraulic amplification type "nozzle-wall" and piezoelectric control



D/ Proportional valve with "disk" type piezoelectric control

Fig. 1. Different types of valve control design [1, 3–5].

The piezoelectric actuators are electromechanical transducers that, thanks to their dynamic characteristics, are suitable for pilot control of high response hydraulic valve with small dead-band. There are two basic types of piezo transducers, according to the class of electro-mechanical actuators to which they belong, they are named: axial and disk.

The impossibility of using piezoelectric transducers as an effective actuator in direct-operated hydraulic devices is a result of both the small working stroke and the presence of steepness in the force characteristic as a function of the working range of stroke. It is therefore more appropriate to use them in control valves of small size to serve for pilot electrohydraulic control of the basic regulating element in a proportional valve.

Piezoelectric actuators do not need electrical power to hold in a certain position, unlike any other electromechanical transducers. This makes the devices in which they are built an energy-efficient.

On the basis of this analysis, the following advantages and disadvantages of the piezoelectric transducers can be summarized:

- Advantages: High positioning accuracy in dynamic mode; High speed performance; No control signal is required to hold in position;
- Disadvantages: Small stroke; Strangeness of the force characteristic; Need for temperature compensation; Powerful electronic amplifier for control of high dynamic processes; Low robust stability; High self-sufficiency [5, 6].

This study aims to demonstrate possibilities to apply virtual prototyping techniques at early stage of design development of piezoelectric actuators for pilot valve of high response hydraulic servo valve. Engineering analyses are applied using developed virtual prototypes that gives results close to expected from physical prototyping [7] and provides data for further design considerations.

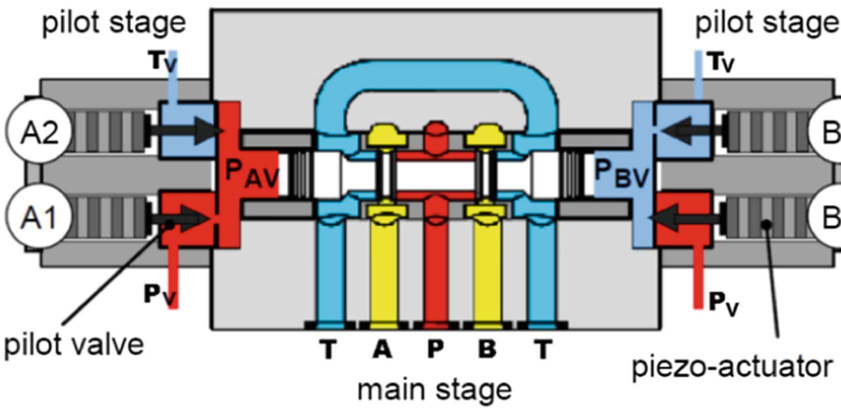
2 Concept Development. Design Considerations

Based on the fact that conventional proportional valves have limited dynamic characteristics, in terms of insufficient sensitivity, precision and high production costs, in most cases makes them not the best choice for applications in high performance systems.

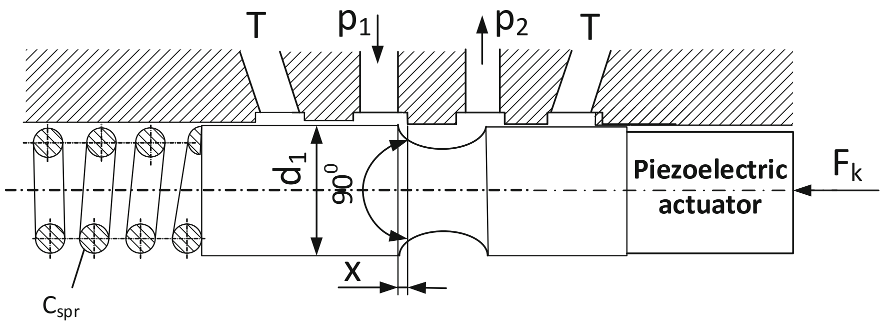
Therefore, a new type of highly dynamic, stability and relatively low cost manufacturing valves are required on the market that can be used in the control of devices in modern hydraulic drive systems.

The use of two-way cartridge valves connected in parallel and PWM (Digital Signal Pulse) (PCM) is one possible alternative to the unconditionally specified requirements, but this is not always appropriate for large linear drives. For this, in the last decade, in parallel with the rapidly developing digital hydraulic devices and systems, the direction of the piezoelectric controlling hydraulic valves has been shaped.

An application of this type of control devices can also be found in more unpretentious hydraulic valves with pilot (indirect) control of the spool shown in Fig. 2. The device has pilot stage that includes four pilot valves, each of 2/2-way type, which is proportionally driven by a piezoelectric actuator. The direct coupling to the actuator provides high stiffness of the pilot stage and thus – a high response of the valve [1, 6].



A/ Proportional valve with “disk” type piezoelectric control [1]



B/ Principal design of control valve with disk piezoelectric actuator

Fig. 2. Schematic presentation of hydraulic valves with pilot (indirect) control

The flow rate through the control valve when the spool valve is fully opened is

$$q = \frac{\Delta V}{\Delta t},$$

where $\Delta V = A_{sp}s$ is a valve displacement and Δt is a switching time. Taking into account that the effective area of the spool is

$$A_{sp} = \pi \frac{d_{sp}^2}{4},$$

where d_{sp} is a spool diameter.

The opening section in function of the stroke of control valve x could be representation as follows

$$S_{sp}(x) = \pi d_1 x \sin\left(\frac{\theta}{2}\right),$$

where d_1 is the control valve diameter in the opening area and θ is the angle of the control valve in the opening area.

The pressure drop in the control valve could be calculated as follows

$$\Delta p_{Loss} = \frac{\rho q^2}{2\mu^2 S_{sp}^2(x)},$$

where ρ is the density of hydraulic oil and μ is the discharge coefficient.

Above equation shows that increase of control valve diameter decreases the pressure drop across the control valve. In opposite, increasing d_1 will lead to increase of the mass and decrease of dynamic parameters of the system.

An additional requirement as to maintain necessary dynamics of the system concerns constant of control valve spring – c_{spr}. Combined with valve mass it needs to assure high operating frequency with maximum force of the piezo actuator F_k and control signal frequency f.

3 Pilot Valve Design. Virtual Prototype

Next step is to develop detailed design of the pilot valve itself, and – its virtual prototype (refer to Fig. 3). Two pilot valves are mounted in a common body (Fig. 3). Each valve consists of a multilayer piezoelectric actuator, developed by Siemens and used in common-rail diesel injectors of PCR2 (pos. 1), valve (pos. 2), disc springs (pos. 3) and set screw (pos. 4), all mounted in a hydraulic block (pos. 5). Developed design has relatively low number of components, but they require specific production technology, especially coating of moving parts as to decrease friction and wear [8].

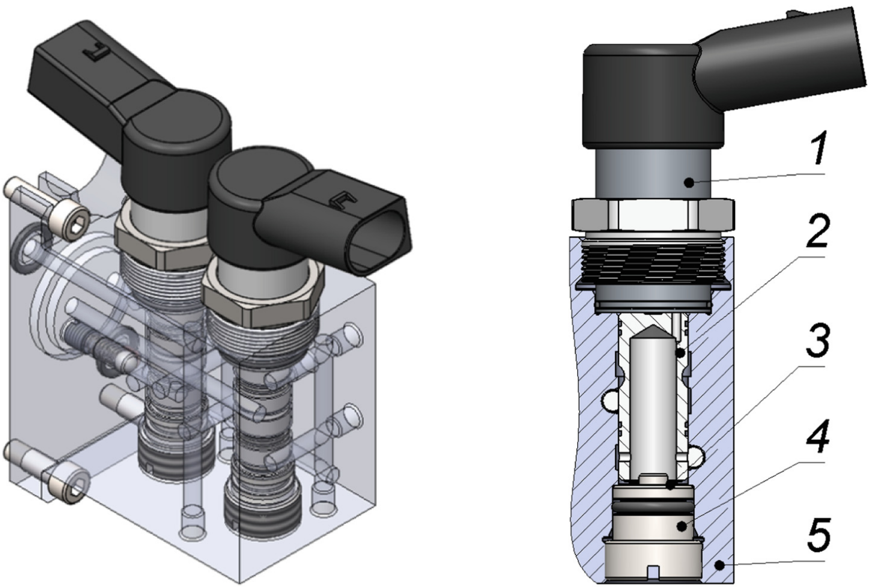
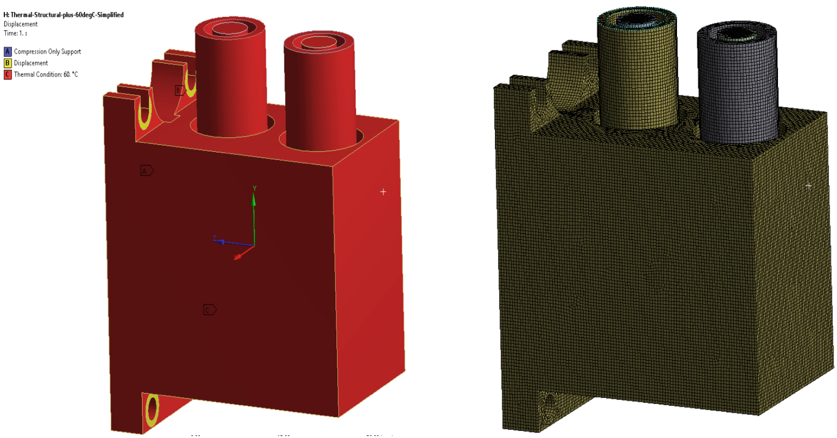


Fig. 3. Design and virtual prototype of the pilot valve.

Prepared virtual prototype is used further for two engineering analyses – under thermal and under pressure – using Finite Element Method (FEM), as to determine maximal deformations of valve and hydraulic block. Relative displacement of these bodies is decisive parameter for pilot valve functionality.

3.1 Engineering Analysis at Thermal Loads

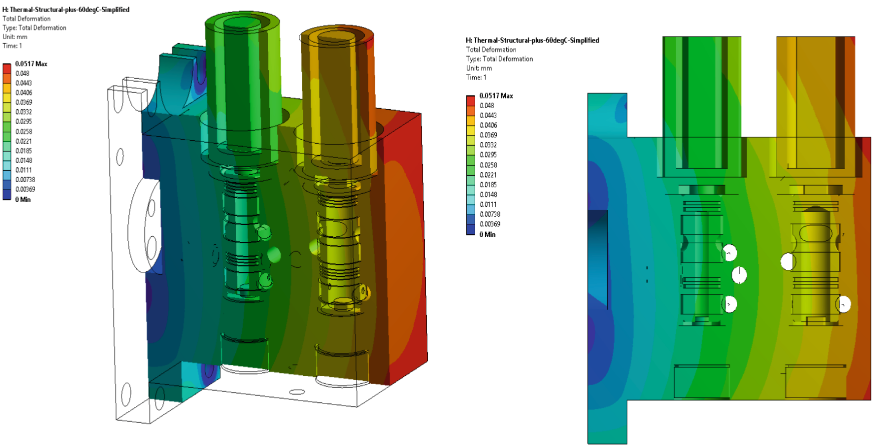
Entire structure is set on temperature of 60 °C and is fixed on its mounting flange, as it is shown on Fig. 4.



A/ Applied boundary conditions B/ Meshed model

Fig. 4. Simulation model used for structural analysis at thermal loads

Simulation results are presented by total deformation distribution fields on Fig. 5.



A/ General view B/ In plane view

Fig. 5. Total deformation distribution fields, mm.

It is clearly seen that there is some difference in valve and block dilatations. An additional calculation shows that this difference is allowable (under 8 µm axially and under 3 µm radially) and thermal loads will not influence significantly work parameters and functionality of examined device.

3.2 Engineering Analysis at Pressure Loads

Next engineering analysis is to check influence of pressure loads. It uses the same meshed model, but different boundary conditions applied (refer to Fig. 6).

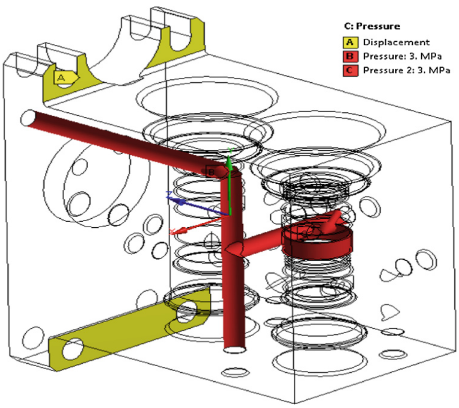
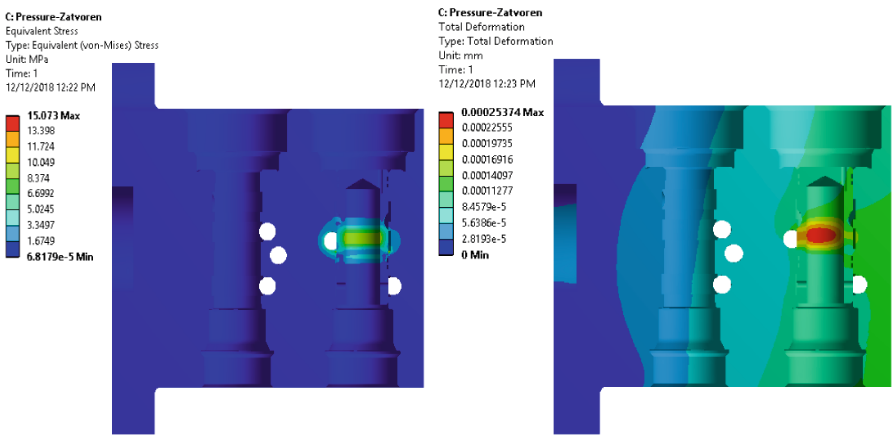


Fig. 6. Pressure loads – applied boundary conditions.

Simulation results are shown for the hydraulic block as it is the major component of interest – on Fig. 7.



A/ Equivalent (von Mises) stress, MPa B/ Total deformation, mm

Fig. 7. Results for hydraulic block, subjected on pressure loads

This design check shows that there are no critical zones that could be found. The deformations are ~ 1 μm and the stresses are insignificant.

3.3 Summary of Engineering Analyses

Both performed engineering analyses – under thermal and under pressure loads – shows sufficient rigidity of the structure that will withstand applied work loads without changing its functional parameters. Developed virtual prototypes are suitable for design optimization as to explore various size ranges [9, 10, 12]. Further design development will be based on physical prototyping and tests, as it is usual in such cases [11].

4 Conclusions

Based on the review and analysis of existing technical solutions concerning the control of hydraulic devices with piezoelectric actuators, as well as on performed engineering analyses over developed virtual prototypes, the following can be summarized:

1. Based on the advantages and disadvantages of the relatively new, for the hydraulic drive equipment, a type of actuators, they are suitable for use in pilot electro-hydraulic control of spool type proportional hydraulic devices (in particular hydraulic valves).
2. To date, the construction of proportional valves and servo valves with piezoelectric actuators includes the presence of a position feedback ("LVTD" type) of the main regulating element therein. This makes them applicable in closed control systems to which systems have high accuracy and performance requirements for executive hydraulic cylinders (motors).
3. The development of hydraulic control devices with piezoelectric control without internal feedback of the main regulating element (spool) implies the introduction of feedback in the executive hydraulic cylinders (motors), which makes them applicable in systems without high requirements for dynamic qualities. However, the practice shows that this leads to complications in the control algorithm.
4. Developed concept for piezoelectric actuators for pilot valve of high response hydraulic servo valve has its design solution and prepared virtual prototype could be used for further technical documentation and physical prototyping.
5. Performed engineering analyses show acceptable results that is not expected to interfere work parameters of the device, and especially – overlapping and opening of the valves. These results are good basis for further product development and are expected to be validated through physical tests.

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