Investigation of a Servo Valve with a Piezoelectric Pilot Stage

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Abstract

Both, the high dynamic requirements, as well as to the control accuracies require special pilot stages for servo valves. Jet pipe or nozzle flapper systems represent the current state of technology. Systems with piezoelectric pilot control could not assert in servo valves. In this article, a direct piezoelectric pilot stage will be presented for a servo valve. The existing nozzle flapper system is compared to with the piezoelectric pilot control system. Furthermore, the possibilities to increase the dynamics are shown.

1. Introduction

Servo valves are generally developed in 2 stages. The first stage converts an electrical signal into a pressure difference signal. This pressure difference affects a second pilot piston and in this way controls the hydraulic energy flow. The regulated servo-hydraulic plants should exhibit a linear frequency response if possible . Commercial 2-stage servo valves such as, for example, the MOOG 76-101, contain a linear frequency response up to approximately 60 Hz [1]. The maximum available power of a 2-stage servo valve should not exceed 22 KW with a system pressure of 280 bar, corresponding to a servo valve with max. 63 l/min. flow. If one would like to command larger energy quantities, either 3-stage or 4-stage servo valves [2] are used. Different versions are used as amplifier systems (pilot control). Thus, for example, flapper nozzle amplifiers, jet pipe amplifiers or beam deflection amplifiers are operated by a torque - engine or a moving coil [3].

For these reasons one tries to control the pilot stage via piezo mechanical actuators [4]. These are characterised by short response times, high setting sensitivity, production of high loads, loss-free maintenance of a position, and are practically without wear. A disadvantage is the low usability stroke of piezo mechanical actuators. Consequently, a direct control has been done without up till now. It has been attempted to reach the desired stroke either with mechanical or hydraulic transmission units [3]. The advantages of high rigidity and thereby also high resonant frequency are thereby however nullified again. In addition the temperature behaviour of the Piezo actuators must be considered. The temperature expansion can be larger than the actual utilisable stroke and must, therefore, be considered in the construction.

A possibility for direct control is via Piezo bending transducers, which represent a system in a Wheatstone bridge circuit [5].

Another possibility for direct control is the use of Piezo stack actuators, which directly affect the pilot piston. In this way all the advantages of the piezo mechanical actuator can be used. The construction must be arranged in such a way however that, despite the low stroke, the pressure yield in the pilot stage is large enough to accordingly influence the main stage. One possibility of direct actuation is shown in [6]. It can be seen that the construction has a short response times. By the direct actuation and the use of only one control edge in the pilot stage the desired flow rate to actuate the main piston is not given.

2. The Piezo Pilot stage

Based on the results of previous developments a piezoelectric pilot stage with six control edges is developed. The pilot stage works as a 3/2 way valve with piezoelectric actuation. To generate a higher flow rate three control edges are used on the inlet side and on the outlet side. Figure 1 shows the construction of the pilot stage. The piston of the valve is built as stage piston to generate a permanent force component in the direction of the piezo actor. This is to prevent a lifting of the piston from the piezo actor. The step piston can be produced as a unit. The tolerances of the individual control edges are for the production a particularly high demands. The tolerances are a result of the stroke of the piezo actor of only 40µm. In figure 1 can be seen that the connection between P-A is carried out with three control edges. The connection between A-T consists of two control edges and one annular gap. The control sleeve is built of different disks to get a precise position of the control edges (see figure 1).

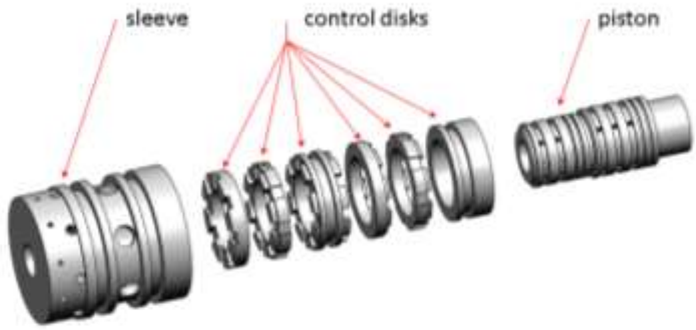

Figure 1: pilot stage (piston and control sleeve)

Figure 2 shows, that always two pilot stages are used to control one main stage. In one pilot stage is P with A connected, in the other stage A with T. The dynamics of the main stage thus results from the maximum volume flow at a certain pressure difference through both pilot stages. Furthermore, impact on the dynamics has the dead volume between the pilot stage and main stage and the mass of the main piston.

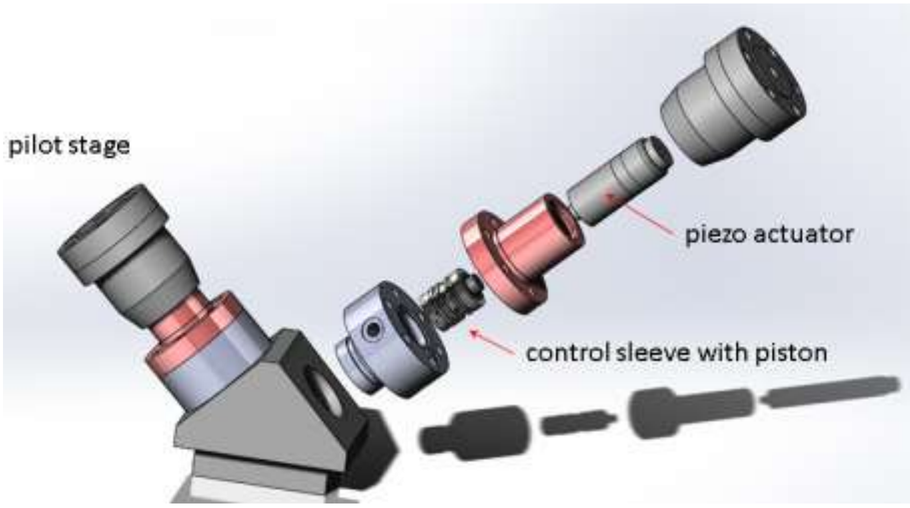

Figure 2: The two pilot stages which are mounted on the main stage

Due to the high dynamics of the piezo actuator, the pilot stage can be operated in PWM-mode. However, it must be considered the maximum heating of the piezo actuators. Another point which must be carried out is the eigenfrequency of the whole system, because the PWM-signal of the piezo actors will generate a oscillating of the system. The flow through the control edge is analytically difficult to calculate [7], so the flow is detected in the pilot valve via measurements and CFD methods.

3. Carried out Investigations

3.1 Thermal load of the Piezo Actuator

Each switching operation of a piezoelectric actuator converts about 5-7% of the energy into heat. How much energy is converted depends on the piezo ceramic (“dielectric loss factor” $\tan\delta$) and of the operating voltage of the piezoelectric actuator. Table 1 shows the specifications of the piezoelectric actuator, which are used to calculate the power loss by equation 1.

$$P_{verl} \approx \tan\delta \cdot f_D \cdot C \cdot {U_D}^2 \quad (1)$$

Table 1: Specifications of the piezoelectric actuator (PIC 151)

	value	unit
cutie temperature	$T_c = 250$	°C
dielectric loss factor	$\tan\delta = 0{,}02$	
specific heat capacity	$HC \approx 350$	J/(kg K)
specific thermal conductivity	$TC \approx 1{,}1$	W/(m K)
electric capacity	$C = 460$	nF

The switching frequency f_D results in different power losses. With these thermal power as boundary condition it’s now possible to calculate by a FEM-calculation the heating of the piezoelectric actuator over the time (see table 2). It can be determined whether a temperature equilibrium with the environment below the maximum permissible temperature of the piezoelectric actuator is possible.

Table 2: Temperature of the piezo actuator in dependence of the switching frequency

frequency Hz	internal heat source W/(mm^3)	temperature of the actuator °C	Temperature of the housing °C	time s
40	0,0001	43	40	5500
500	0,0007	62	43	4000
750	0,0010	72	46	3900
1000	0,0014	85	50	4000
2500	0,0035	154	64	2000
3750	0,0052	210	77	2000
5000	0,0069	250	68	477
7500	0,0104	250	53	122
10000	0,0139	250	50	65

3.2 Calculation of Eigenfrequency of the Whole System

As main stage is a proportional valve of the company Moog used [8]. To calculate the eigenfrequency the piston of the main stage, all the oil volumes and the piezo pilot stage are loaded as mesh in a FEM simulation. For simplicity all individual volumes are arranged in succession. For changes in diameter of the oil volume massless infinitely rigid disks are used (see figure 3).

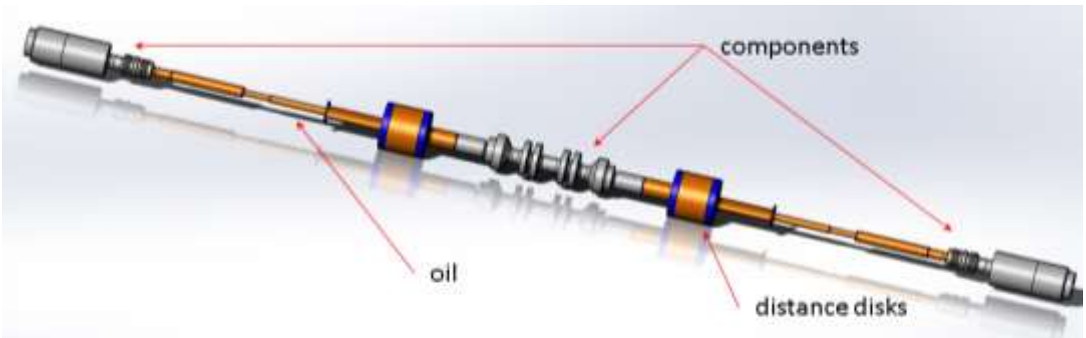

Figure 3: Modell to calculate the eigenfrequency

The eigenfrequency of the whole valve stage could be determinate with 1 kHz (see figure 4). Accordingly, the switching frequency of the PWM signal should be either below or above 1 kHz. In respect to the heating of the piezoelectric actuator a frequency below 1 kHz should be selected.

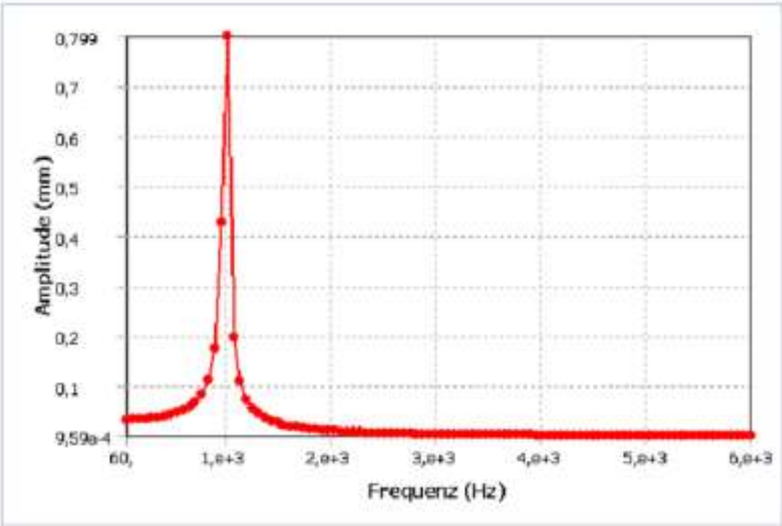

Figure 4: Eigenfrequency of the whole valve

3.3 Determination of the Volume Flow in the Pilot Stage

In order to estimate the dynamics of the main stage the volume flow in the pilot stage is determined. As a restriction the compression volume of the oil is not considered. According to figure 1 the pilot stage consists of three orifices in the connection P-A and two orifices and one annular throttle in the connection A-T. At a supply pressure of 200 bar, this pressure must be dismantled from P-A-T in the two pilot stages. With the analytical equations for the orifice and the annular throttle (see equation 2 and 3) [9] a pressure-flow diagram can be calculated (see figure 5).

$$Q = \alpha \cdot A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \qquad (2)$$

$$Q = \frac{\pi \cdot d_m \cdot h^3 \cdot \Delta p}{6 \cdot (d_a - d_i) \cdot \eta} \qquad (3)$$

In equation 2 we can find the orifice factor α. These represent the biggest factor of uncertainty for the calculation [7]. To counteract this, a pressure-flow characteristic was measured for the connection P-A. For the connection A-T the orifice factor was based on the measurement of the connection P-A adapted. Furthermore the leakage of the valves must be determined. This is also performed by a measurement (see figure 6).

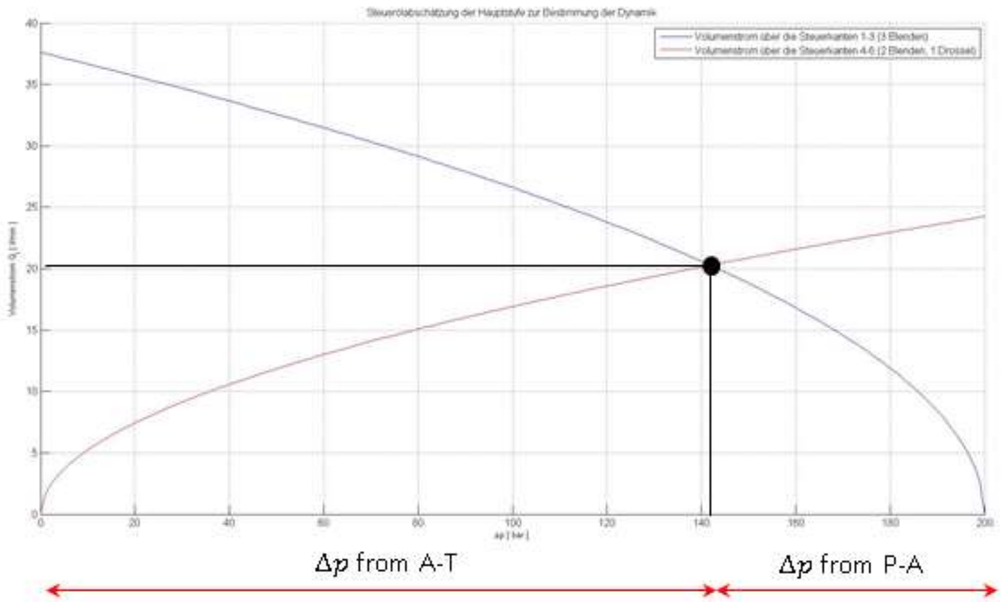

Figure 5: Analytic calculation of the volume flow through the pilot stage

Accordingly, the operating point for the main stage at maximum opening of the pilot stage results at 8,3 l/min and 133 bar for the main piston. These values are compared with the measured step response of the main stage of the valve with 7,2 l/min and 133 bar. The difference of 1,1 l/min can be explained by the limitations in determining the flow and the mass of the main piston at the step response.

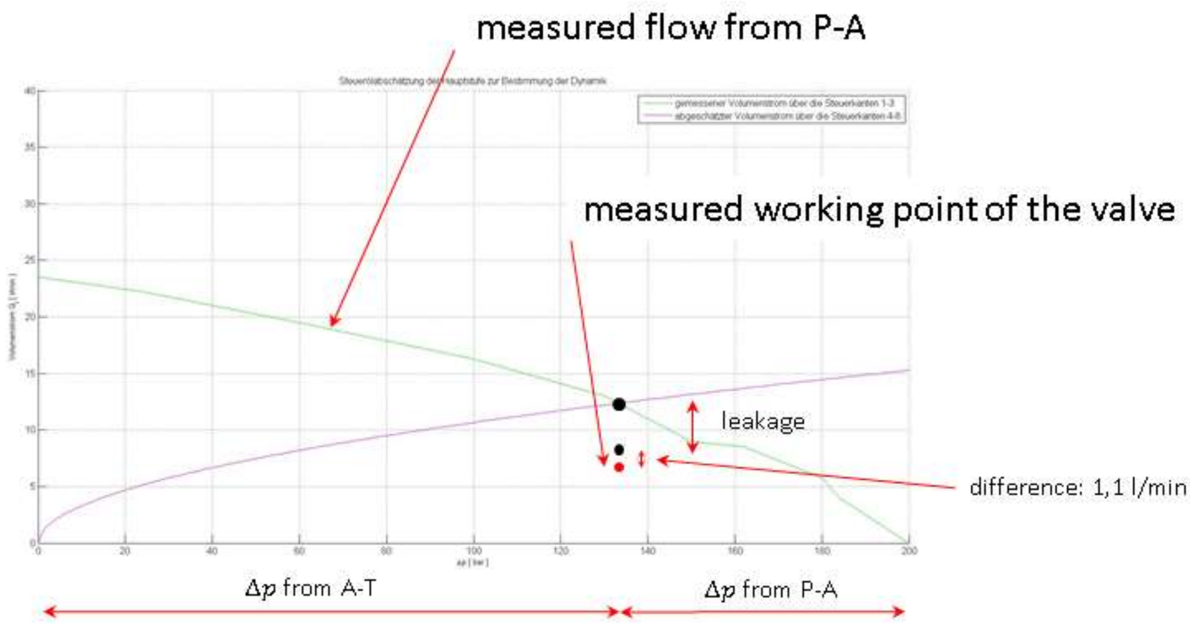

Figure 6: Measured volume flow through the pilot stage

4. Conclusion

Care must be taken in designing the pilot stage with piezo actuators that the heating of the actuator is not to high. The hoped increase in dynamic by the use of a directly operated pilot stage and six control edges could not be satisfied. The short stroke of the piezoelectric actuator is still a problem. A translation of the stroke would again mean restrictions in the dynamics and at the eigenfrequency of the valve. A way translation of the stroke of the piezo actuator while maintaining rigidity of the pilot stage would be the most optimal solution.

5. References

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