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Piezoelectric Actuation in a High Bandwidth Valve

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To expand the operational capabilities of hydraulically actuated systems the development of new valves capable of enhanced flow rates and bandwidth performance is required. In previous work, the solution to achieving desired flow rates was to increase valve spool size and travel, but this is at the expense of the dynamic response. To increase flow without restricting dynamic performance, this paper proposes the use of multiple metering edges achievable using the Hörbiger plate valve principle, actuated by piezoelectric means. Experimental results from a piezoelectric actuated valve are then used to demonstrate improved performance in both static and dynamic operation.

Keywords Piezoelectric; hydraulic valve design; actuation; bandwidth; Hörbiger

1. Introduction

In modern industrial and science based environments there is a need to improve and expand the operational capabilities of hydraulically actuated machine systems. Such systems are capable of delivering large forces over long strokes e.g. 3 metres in the opening of the UK Gateshead Millennium Bridge. However, the operational bandwidth is relatively low, typically less than 100 Hz. In comparison, a piezoelectric actuation system generally has a much lower stroke and relatively high force capabilities over higher bandwidths. An ideal hydraulic actuator would achieve high performance standards for in terms of force levels, dynamic range of operation, stroke range, and precision. At present no such actuation system exists.

The operational capabilities of hydraulically actuated systems would be improved with the development of new valves capable of enhanced flow rates and with higher bandwidth. Previously, the technical challenge in developing such valves was the need for large spool strokes used to achieve the desired flow rates, but this hinders the valve dynamic response [1]. To increase flow without hindering dynamic performance the use of multiple metering edges is proposed. This is achievable using the Hörbiger plate valve principle with an integrated high bandwidth piezoelectric multilayer actuator [2, 3].

Winkler and Scheidl [4] have previously proposed the use of multiple metering edges made possible using the Hörbiger plate valve principle, which is commonly found in compressor applications [5–7]. The advantage of the Hörbiger plate operation is that the necessary spool stroke can be greatly reduced, thus improving dynamic valve response. The use of this principle in combination with a hydraulically piloted on/off valve allowed

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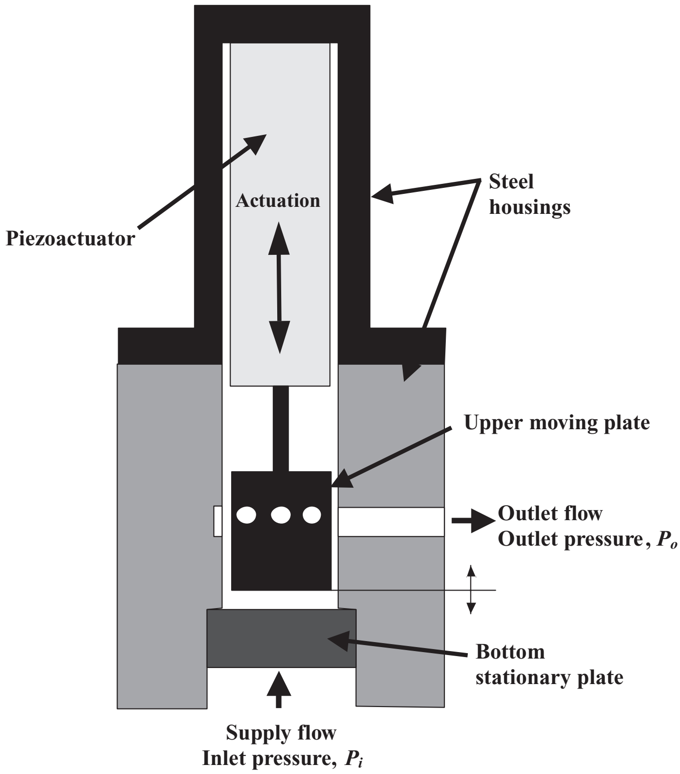

Figure 1. Simple schematic of constructed valve under a pressure drop of $\Delta P = P_i - P_o$ (valve shown in open position).

for flow rates up to 100 L/min for a 5 bar pressure drop across the valve, and mechanical opening times from 1.5 ms with a 2 ms electronic and mechanical pilot delay [4].

Since piezoelectric actuators have high bandwidth capability their use would greatly improve the valve opening time, and allow for proportional control of the moving components. However, the valve seat for the Winkler and Scheidl [4] design had to displace 0.6 mm, while the maximum direct displacement of a piezoelectric actuator is generally smaller due to the relatively low maximum strain capability of piezoelectric devices (~0.1%) [8]. By increasing the number of metering edges it is possible to reduce the necessary opening of the valve and allow for direct piezoelectric actuation of the plate.

The design and construction of a valve utilizing these principles has been undertaken at the University of Bath. The valve is a normally open valve with the piezoelectric actuator connected directly to an upper moving Hörbiger plate, while the lower plate is stationary (Fig. 1). This paper presents experimental results from a piezoelectric actuated valve with the intention of demonstrating performance in both static and dynamic domains.

2. Hörbiger Plate Concept

The Hörbiger plate principle is based on the use of annular grooves in two mating plates. These are used to form multiple metering edges which allow for large flow path areas at relatively small plate separation distances [4–7]. When the plates are separated, fluid will

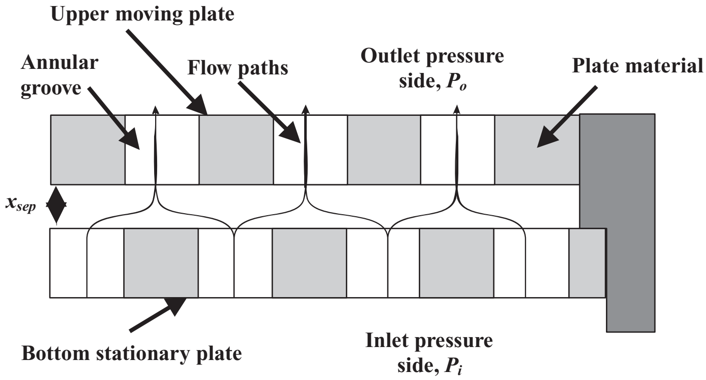

Figure 2. Simple schematic of flow through the annular grooves with plates separated under a pressure drop of $\Delta P = P_i - P_o$ (valve shown in open position).

move through the grooves as shown in Fig. 2. The use of multiple rings greatly increases the overall flow area possible in comparison to traditional poppet and spool configurations, allowing for large flow rates to be achieved at relatively low pressure drops, ΔP. The pressure drop is defined as the pressure on the inlet side of the valve, P_i, minus the pressure on the outlet side, P_o, as indicated in Figs. 1 and 2.

The upper plate consists of a hollow piston with annular grooves on the lower face. The grooves connect to the chamber inside the piston via multiple holes, and radial holes allow the flow to pass to the outlet port. Flow rate is controlled by the distance between the two plates, with a residual leakage flow when the plates are in contact. Maximum flow occurs when the plate separation is approximately one half of the annular groove width [4]. The smaller the groove width the smaller the necessary plate separation and the faster the achievable dynamic opening time for the valve. The performance of the Hörbiger plate principle is therefore limited by manufacturing precision, oil contamination and fluid friction effects if the grooves are too small [4].

3. Valve Design

Figure 1 shows a schematic of the completed valve. The valve is designed as a 'normally open' valve with a multi-layered piezoelectric lead zirconate titanate (PZT) actuator directly controlling the upper moving plate (Physik Instrumente part no. P-225.4s). The moving plate opposes a stationary lower plate when the piezoactuator is fully extended under an applied voltage, and plate separation occurs as the applied voltage is reduced and the piezoelectric actuator displacement is decreased. The piezoactuator used in the valve has a 12.5 kN blocking force at zero displacement, and is preloaded by 2 kN. The 2 kN preload was chosen to ensure that if P_o exceeds P_i the piezoelectric actuator would have sufficient preloading to avoid tensile loading damage. The maximum displacement of the piezoelectric actuator is 68 μm at an input voltage of 1000 V. To power the piezoactuator a high power amplifier (Physik Instrumente part no. E-481.00) was chosen to supply up to 2 A at 1000 V with -3 dB drop-off in supply current at approximately 550 Hz for the actuator used.

The force capacity of a piezoactuator has a linear relationship to its displacement, with maximum stall force occurring at zero displacement and zero force produced at maximum

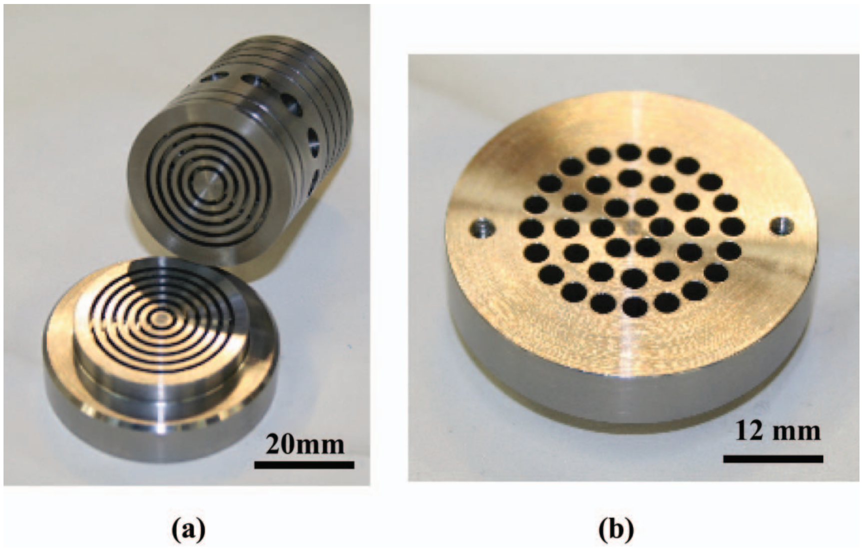

Figure 3. (a) Image of annular grooves on the Hörbiger plate (b) Image of the underside of the bottom stationary plate showing supply holes.

displacement [9]. Through experimental testing it was determined that the housing of the valve inevitably deflects to some extent due to the pressure acting on the upper plate and on the housing. It was therefore necessary to limit the upper moving plate displacement to 43 μm when there was no fluid pressure on the supply side. This implies that with no fluid pressure in the system the piezoactuator will need to displace by 43 μm to close the valve. This was undertaken to ensure adequate piezoactuator force and displacement to keep the flow paths closed under desired operating pressures.

The Hörbiger plates are designed with flat faces and have six annular grooves on the lower stationary plate and five grooves on the upper moving plate. The grooves are 1 mm wide and the final manufacturing precision resulted in a slight underlapping of the valve, which meant there was a residual leakage flow when closed. Supply flow enters from the bottom of the valve, and exits from the side, as shown by the flow lines in Fig. 2.

Figure 3 shows the completed plates. To supply flow to the annular grooves shown in Fig. 3a holes have been positioned in the opposing surface of the poppet. This allows flow to pass through the grooves, while maintaining structural strength and rigidity of the plates (Fig. 3b). Computational fluid dynamics (CFD) simulations were completed using ANSYS CFX and it was found that flow through these holes had a negligible effect on the overall flow/pressure characteristics (less than 0.3 bar pressure drop for a flow rate of 40 L/min).

4. Experimental Results

Valve experiments were undertaken to evaluate both the steady state and dynamic response characteristics for the constructed valve. Piezoresistive pressure sensors (Kulite part no. ETM-375) were located at the inlet and outlet to the valve and a turbine flow meter was located on the outlet. Steady state plate separation was measured directly using a position sensor (Techni Measure part no. MG-DVRT-3) located on the upper moving plate. Nominally this sensor measures the total separation between the plates (x_{sep} in

Fig. 2) due to the displacement of the piezoactuator, allowing for housing compliance. Although the sensor is capable of measurements up to 7 kHz, due to space limitations it was not possible to directly connect it to the upper moving poppet, and it only rests on it. In addition, there is significant noise that can be filtered out for steady state results, but makes dynamic measurements of the plate separation unreliable. Piezoelectric actuator displacements are determined using strain gauge sensors built into the actuator. A dSPACE® real-time interface system was used for measurement and control purposes to account for the hysteretic voltage-displacement relationship for the actuator.

4.1 Steady State Performance

Figure 4 shows the steady state flow characteristics for the valve as a function of plate separation and pressure drop (ΔP) across the valve. Plate separation was held constant using a simple Proportional-Integral controller based on feedback from the sensor located on the upper moving plate. This was necessary as compliance in the housing due to changes in ΔP required the piezoactuator to vary its extension. The 69 L/min limit of the hydraulic fluid supply is also indicated in Fig. 4 to show the maximum possible flow rate. It can be seen that flow increases as the pressure drop and plate separation distance increase. At a plate separation of 40 μm a flow rate of 55 L/min is achieved at pressure drop $\Delta P = 7$ bar, while at a separation of 20 μm a flow rate of 27 L/min is achieved for the same ΔP. The Reynolds number is low (<100) due to the small plate separation and the flow-pressure characteristics are nearly linear.

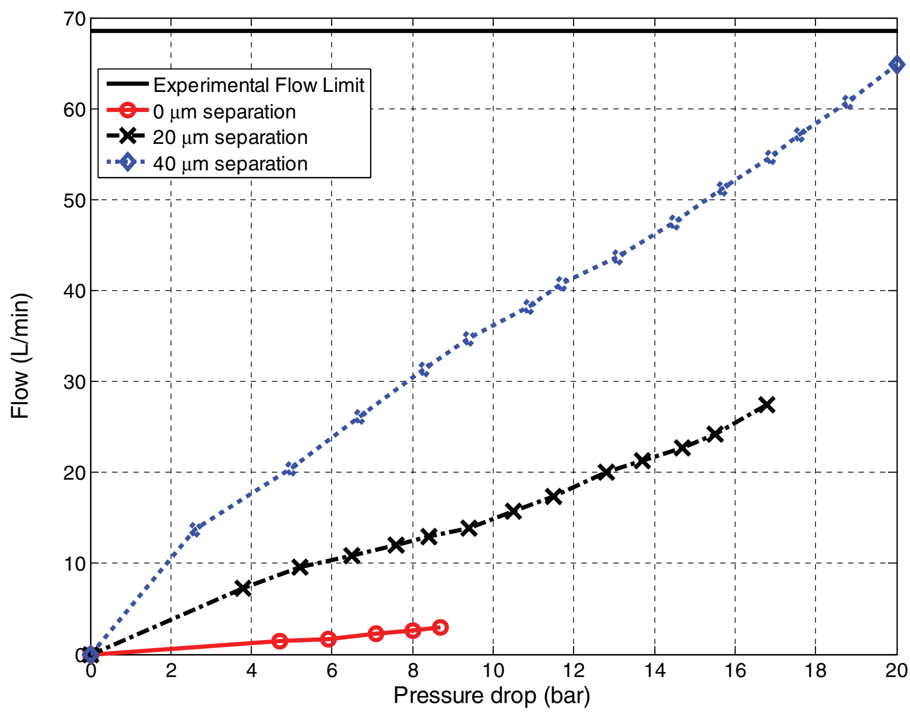

Figure 4. Steady state flow characteristics for the valve as a function of plate separation and pressure drop across the valve.

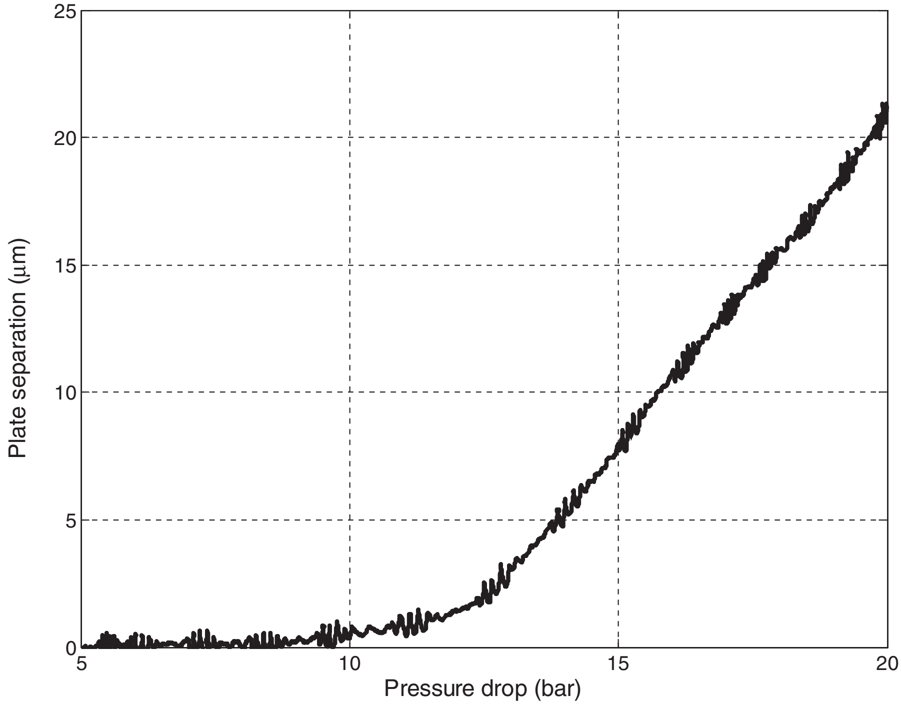

Figure 5. Measured separation of the plates as supply pressure is increased with 1000 V applied to piezoactuator.

The maximum cracking pressure is the pressure where the force due to P_i acting on the upper moving plate exceeds the opposing forces due to P_o and the maximum force from the piezoelectric actuator (1000 V input at 43 μm displacement), thus causing the plates to separate. In hydraulic valves this is important as it determines the maximum operating pressure at which the valve can be closed and flow shut off. To determine cracking pressure the maximum voltage was applied to the piezoactuator (1000 V), and supply pressure slowly increased until plate separation occurred as measured by the steady state position sensor located on the upper moving plate.

Figure 5 shows that the pressure forces acting on the upper moving plate will exceed the force and displacement characteristics of the piezoactuator at approximately $\Delta P = \sim 9$ bar. Simulations have shown that with an infinitely stiff housing the cracking pressure of the valve in its current configuration is approximately $\Delta P = \sim 50$ bar. The difference is due to compliance of the valve housing; the piezoactuator needs to extend to compensate for this compliance, reducing the available force. Decreasing the allowed maximum displacement of the upper moving plate when there is no pressure in the system would increase the cracking pressure, but would reduce the maximum plate separation possible for given operating pressures. The harmonic ripple in the data in Fig. 5 is due to electronic sensor noise arising from the piezo amplifier.

4.2 Dynamic Performance

The piezoelectric actuator strain gauge enables high bandwidth measurement of the displacement of the actuator. This is related to the separation of the plates, but is not the same

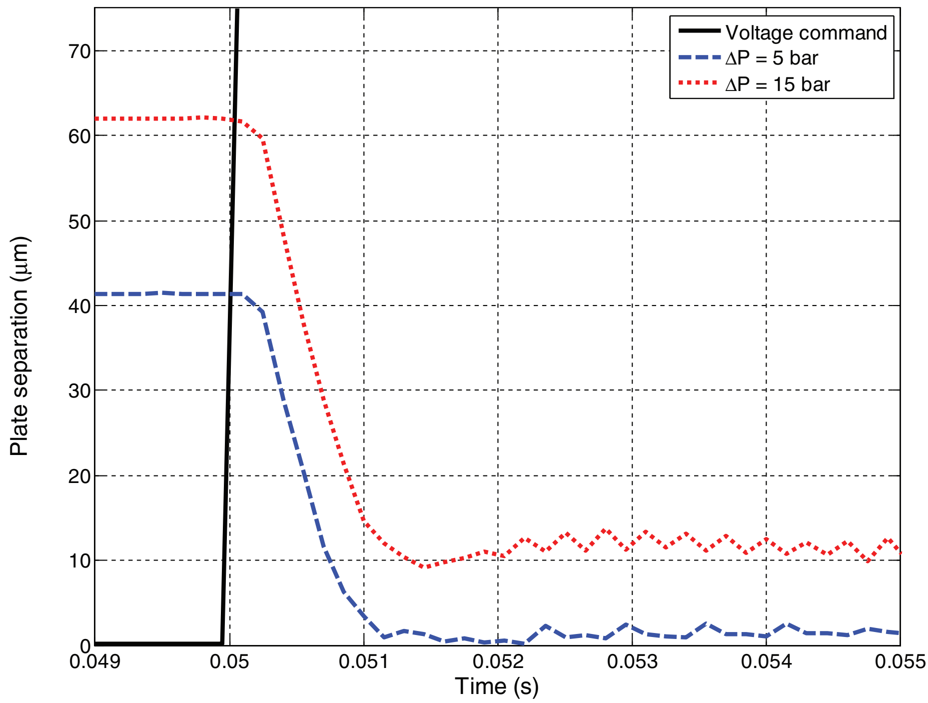

Figure 6. Plate separation as a function of time for varying values of ΔP across the valve—Piezoactuator commanded to extend (0 V to 1000 V input) at time = 0.05 s thus closing the valve.

because the separation of the plates is affected strongly by compliance of the valve housing. Since it is not possible to directly measure dynamic plate separation with the current sensor arrangement, the dynamic separation can be inferred using the steady state plate separation position sensor and piezoactuator strain gauge displacement:

$$x_{sep} = \left| \left(\frac{x_{sepT}}{x_{pT}} \right) \left(x_{pstop} - x_p \right) \right| + x_{icls} \tag{1}$$

where x_{sep} is the dynamic separation distance between the plates (Fig. 2), x_{sepT} is the total steady state separation distance over the test, x_{pT} is the total piezoactuator displacement, x_p is the current strain gauge displacement, x_{pstop} is the maximum displacement of the piezoactuator when unloaded (68 μm), and x_{icls} is the initial steady-state displacement of the plate when the piezoactuator is fully powered (1000 V). This equation is approximate as the effect of dynamic force variations is not considered, but it gives a good indication of the speed of closure.

Figure 6 shows the plate separation response for a voltage step-command applied to the piezoelectric actuator to close the valve. This was accomplished by switching the power supply to the piezoactuator from a maximum of 1000 V to 0 V at 0.05 s. It can be seen that the time to achieve minimum plate separation for the valve will increase from approximately 1 ms at $\Delta P = 5$ bar to 1.1 ms at $\Delta P = 15$ bar. This is due to the increased pressure forces on the moving plate acting to resist closing of the valve. It can also be seen that the valve does not completely close due to fluid compression between the plates at the edges and housing compliance under cracking pressure. The apparent rise in separation

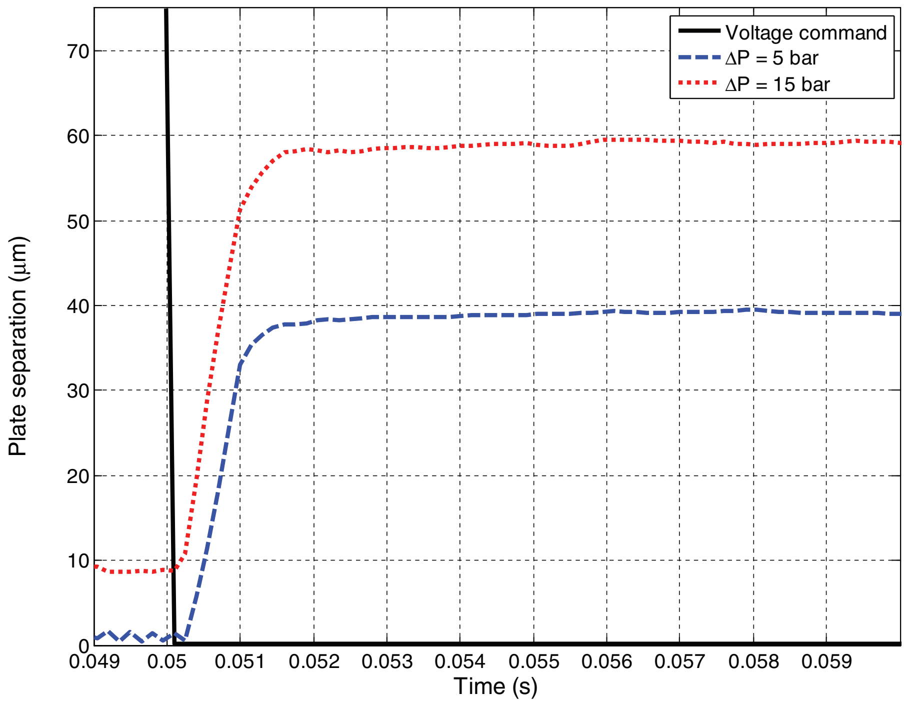

Figure 7. Plate separation as a function of time for varying values of ΔP across the valve—Piezoactuator commanded to retract (1000 V to 0 V input) at time = 0.05 s thus opening the valve.

after first closure is probably due to a surge in pressure during closure. At $\Delta P = 5$ bar the valve should have fully closed.

Figure 7 shows the plate separation response for a voltage step command to open the valve (1000 V to 0 V). It can be seen that increasing ΔP across the valve will increase the rate at which the valve opens. However, due to compliance in the housing the maximum displacement of the upper moving plate is also increased, so the overall time to open is approximately the same at 1.5 ms. This increase in opening rate is due to the fact that the supply pressure forces are assisting the motion of the moving plate. It can also be seen that the valve does not start from the fully closed position at $\Delta P = 15$ bar due to housing compliance causing the valve to be opened under cracking pressure.

The piezoelectric actuator and upper moving poppet were removed from the valve for bench tests to determine frequency response using an "ideal" high performance power amplifier. From this a first natural frequency of 2.8 kHz was determined for the piezoactuator and added mass. However, calculations for the power amplifier used in the valve testing, based on the 2 A limit and voltage and capacitance requirements, show a drop-off in performance at ~550 Hz [3]. This shows that the limiting factor on dynamic valve performance is likely to be due to the electric current limitations of the power amplifier used in the valve and not limitations in the piezoactuator.

5. Conclusions

This paper has presented the experimental results of an integrated hydraulic/piezoelectric valve design. It shows that excellent valve flow performance can be obtained though the use of the Hörbiger plate method. This allows for an increase in flow across a valve, while decreasing the necessary plate separation, by increasing the number of metering edges available. Since piezoelectric actuators are ideally suited for small displacements at high frequency the dynamic performance of the valve is then improved by directly connecting a piezoactuator to the moving parts.

The steady state characteristics of the valve have been evaluated to show that large flow rates can be obtained for very small plate separation distances. These were up to 66.5 L/min at a $\Delta P = 20$ bar and 40 μm plate separation. Decreasing the plate separation distance or pressure drop across the plates reduces steady state flow. The use of a piezoelectric actuator was also shown to allow for precise proportional control of the valve opening.

Finally, the dynamic response of the valve to a step command was evaluated. It was found that the time to close the valve will increase from approximately 1ms at $\Delta P = 5$ bar to 1.1 ms at $\Delta P = 15$ bar. The time to open the valve was approximately 1.5 ms regardless of ΔP. However, the rate of opening and final plate separation distances increased with ΔP. The valve constructed by Winkler and Scheidl did allow for higher flow rates of up to 100 L/min at $\Delta P = 5$ bar. However, the dynamic performance for their valve was slower in comparison, where the fastest total valve opening time was 3.5 ms, and the fastest closing time 3.2 ms [4].

It has been shown that the use of the Hörbiger plate principle in combination with direct piezoactuation of the parts can be used to achieve improved static and dynamic hydraulic valve performance. The components and methodology developed can be used to improve smart actuation applications in areas such as extrusion and injection moulding machines, vibration test machines, flight control surface adjustment in aircraft, positioning in robotic systems, and active vibration/noise attenuation.

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