Digital Control of Electrorheological Valves


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Digital Control of Electrorheological Valves

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Abstract: The idea to replace continuously adjustable proportional valves by a certain number of simple on/off valves emerged by the name digital hydraulics. Theoretical and practical examinations have shown the usefulness of this concept. This contribution is concerned with the adaption of digital hydraulics to electrorheological (ER) valves. Based on a mathematical description of continuously adjustable ER valves, a new construction of a digitally controlled ER valve is presented. The proposed construction is distinguished by its very compact and simple design in comparison to digital hydraulic systems based on conventional valves. The proposed digital ER valve is tested on an optical ER valve test stand. Static and dynamic measurements show a good performance and hence the practical applicability of the proposed approach.

Keywords: electrorheological valve, digital valve control, electrorheological fluid, structured electrode, digital hydraulics.

1. INTRODUCTION

Fast continuously adjustable servo or proportional valves are normally used in hydraulic applications with high demands on the accuracy and the bandwidth. In recent years it has been shown that also electrorheological (ER) valves are well suited for active and semi-active applications with fast dynamics, see e.g. Choi and Cho (2005) and Kemmetmüller and Kugi (2004) for servo drives and Song et al. (2003) and Kugi et al. (2005) for shock dampers. In conventional hydraulic valves the volume flow is controlled by opening or closing an orifice by means of a spool. In contrast, the volume flow is directly controlled by changing the apparent viscosity of the electrorheological fluid in an ER valve. This is done by applying a sufficiently large electric field to the ER fluid. Typically, the ER fluid is a suspension of polarizable particles in a fluid phase. Under the presence of an external electric field the particles form chains along the direction of the electric field, cf. Parthasarathy and Klingenberg (1996), which cause the change of the apparent viscosity of the ER fluid. The ER effect is reversible, can be continuously controlled and exhibits a very fast response time of a few milliseconds. The simple construction of ER valves in the form of two electrodes forming a flat gap is a major advantage in comparison to conventional valves. There is, however, the need for a linear high voltage amplifier in order to continuously adjust the volume flow through the ER valve.

The idea of approximating the functionality of conventional proportional valves by a number of on/off valves is well known in conventional hydraulics and was probably introduced in the patent of Rickenberg (1930). After years of little practical or theoretical activity, in 2001 a group at Tampere University of Technology seized the concept and funded the name *digital hydraulics*, see Linjama et al. (2003). The main idea of digital hydraulics is to use several adequately sized on/off valves in parallel instead of one proportional valve. In combination with a digital control strategy it is possible to adjust the volume flow of this digital valve over a wide range and a sufficient accuracy. Feasibility and usefulness of this concept has been shown by means of practical applications, see, e.g., Linjama et al. (2003) and Laamanen et al. (2007) for the position control of hydraulic cylinders. The stated benefits of digital hydraulics are low cost, robust valves, energy efficiency, fault tolerance, no spool position feedback and amplitude-independent fast response time. In contrast to this there are a number of drawbacks in comparison to conventional proportional or servo valves, see, e.g., Linjama et al. (2003) and Linjama and Vilenius (2007): (i) Due to the finite number of on/off valves, a jerky motion can occur in hydraulic drives. (ii) The fast switching of the on/off valves causes pressure peaks in the system. (iii) Manufacturing tolerances and the different dynamics of the on/off valves can result in output and step uncertainties.

Applying the idea of digital hydraulics to ER valves allows to circumvent some of these drawbacks. The simple construction of an ER valve allows for the usage of a higher number of (on/off) valves than in conventional hydraulics. Furthermore, it is simpler to guarantee small manufacturing tolerances and the dynamics of ER valves is basically independent of the size. Finally, instead of using expensive linear high-voltage amplifiers, the high voltage only has to be switch on and off. This also significantly reduces the systems costs. Thus, the topic of this contribution is the design and the test of digital hydraulic valves based on ER valves.

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The paper is organized as follows: In Section 2 the mathematical modeling of continuously adjustable ER valves is presented. Based on the derived model, constructions of digital ER valves are proposed in Section 3. The performance of a digital ER valve is validated by means of measurement and simulation results in Section 4. Finally, in Section 5, a short summary and an outlook to future research activities is given.

2. MATHEMATICAL MODEL OF AN ER VALVE

In this section the mathematical model and the basic functionality of a continuously adjustable ER valve is discussed. In general, an ER valve consists of an flat (or annular) channel of height H, which is formed by two electrodes of length L and width W, see Fig. 1. If a pressure difference Δp between the inlet pressure p_i and the outlet pressure p_o is present, a volume flow q of the ER fluid takes place. By applying a voltage U to one electrode while the other electrode is connected to ground, an electric field $E = U/H$ is generated which is used change the rheological properties of the ER fluid.

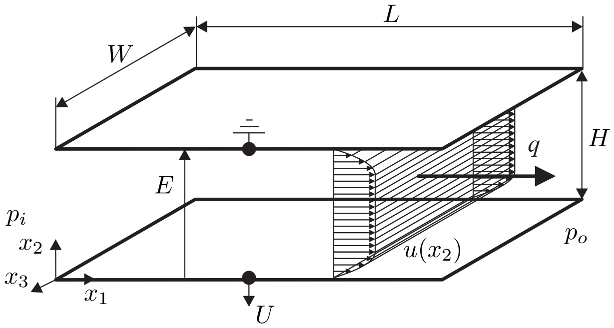

Fig. 1. Flat channel ER valve.

In most cases the ER fluid is a suspension of polarizable particles in a fluid phase. In order to describe the behavior of the ER fluid in response to an electric field E, models describing the microscopical behavior of the particles have been developed, see, e.g. Parthasarathy and Klingenberg (1996) or See (2004). These models are, however, not suitable for the modeling of an ER valve, since much computational effort is necessary. Thus, the mathematical models of ER valves are commonly based on the description of the behavior of the ER fluid in the framework of continuum mechanics. Here, a generalized Cauchy stress tensor is used, which incorporates the electric field, cf. Růžička (2000), Rajagopal and Wineman (1992). The general constitutive equation for this Cauchy stress tensor can be simplified for the given flat channel geometry and the following assumptions: (i) the fluid is isotropic, incompressible, has a negligible density and a constant temperature, (ii) the flow in the ER valve is laminar and (iii) the dynamics of the ER effect can be neglected. Then, an extended Bingham material model of the form

$$\sigma_{12} = \tau_0(E)\mathrm{sign}(\dot\gamma) + \eta\dot\gamma \quad \text{if} \quad \dot\gamma \neq 0, \tag{1}$$

with the field strength dependent yield stress $\tau_0(E)$, the shear rate $\dot\gamma = \partial u(x_2)/\partial x_2$ and the dynamic viscosity η of the ER fluid for $E = 0$, can be derived. Based on measurements, the following equation is used for the approximation of $\tau_0(E)$.

$$\tau_0(E) = \begin{cases} a_1E + a_2E^2 + a_3E^3 & \text{if} \quad E < \bar E \\ b_0 + b_1 E & \text{else} \end{cases} \tag{2}$$

Therein, the constant parameters a_1, a_2, a_3, b_0 and b_1 are obtained from measurements, see Fig. 2 for the characteristics of a typical ER fluid.

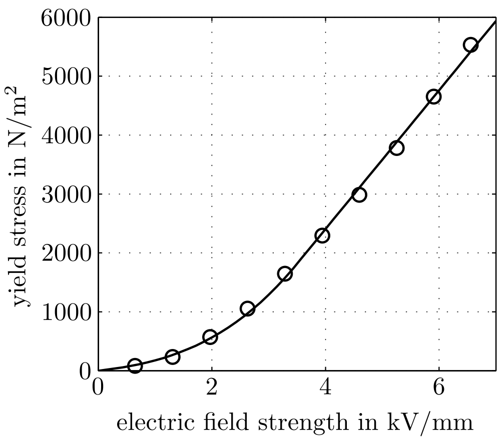

Fig. 2. Comparison between the model and measurements of the field dependent yield stress $\tau_0(E)$ of a typical ER fluid.

The static velocity profile $u(x_2)$ of the ER fluid results from the balance of momentum

$$\frac{\partial}{\partial x_2}\sigma_{12} = -P, \tag{3}$$

with the pressure gradient $P = (p_i - p_o)/L$ and no slip boundary conditions $u(0) = u(H) = 0$ at both walls, see e.g. Kugi and Kemmetmüller (2006) for a detailed derivation. If no voltage is applied to the electrodes ($E = 0$), the material law (1) is purely Newtonian and hence the well-known parabolic velocity profile is obtained. For non-vanishing but moderate electric field strengths, a plug zone in the middle of the velocity profile occurs (see Fig. 1). If the field strength depend yield strength $\tau_0(E)$ is larger than $PH/2$, the plug zone covers the whole gap and the ER valve is closed. The volume flow q through the ER valve is obtained by integration of the velocity profile $u(x_2)$ over the cross-section of the channel.

$$q = \begin{cases} \dfrac{W(PH+\tau_0)(PH-2\tau_0)^2}{12\eta P^2} & \text{if} \quad \tau_0 \le \dfrac{PH}{2} \\ 0 & \text{else} \end{cases} \tag{4}$$

In Fig. 3 the pressure-volume flow characteristics of an ER valve with height $H = 0.75$ mm, width $W = 40$ mm and length $L = 70$ mm is given as function of the applied voltage $U \in [0, U_{max}]$, where $U_{max} = 4$ kV is the maximum voltage. The work space of the continuously adjustable ER valve is then given by the gray shaded area.

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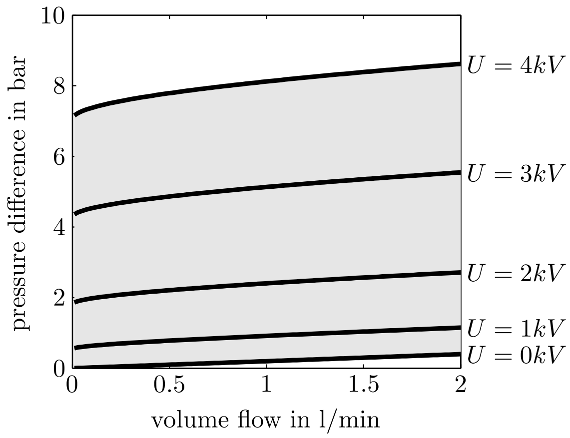

Fig. 3. Characteristics of a continuously adjustable ER valve.

3. DIGITAL ER VALVES

As already outlined, the main idea of digital hydraulics is to approximate the functionality of continuously adjustable proportional valves by a number of independently controllable on/off valves. For this purpose, a number of n on/off valves is connected in parallel, cf. Fig. 4. The overall volume flow of the digital valve is given by

$$q = \sum_{j=1}^{n} q_j(\Delta p) s_j, \tag{5}$$

where $s_j \in \{0, 1\}$ indicates if the corresponding valve is open or closed. By a suitable choice of the size (i.e. the effective opening area) of the valves it is possible to cover a wide volume range by a small number of valves. If a binary coding of the size of the valves is chosen, then the volume flows read $q_j = q_B 2^{j-1}$, $j = 1 \ldots n$, where q_B denotes the volume flow of the smallest valve. The main difficulty in designing such a digital valve are the high demands on the manufacturing accuracy and the timing of the valves.

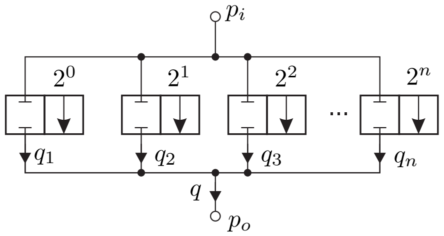

Fig. 4. Basic concept of digital hydraulics.

The adaption of the concept of digital hydraulics to ER valves is straightforward since the volume flow (4) of an ER valve is a linear function of the valve's width W. Thus it is only necessary to scale the width of the individual ER valves according to $W_j = W_B 2^{j-1}$ with the width W_B of the smallest valve. Figure 5 depicts a possible construction of a parallel digital ER valve with $n = 3$ bits. The control of these ER valves is carried out in the form $U_j = (1 - s_j) U_{max}$, with the constant voltage U_{max} and the switches (transistors) $s_j \in \{0, 1\}$, $j = 1 \ldots n$. The overall volume flow through the parallel digital ER valve reads as $q = z q_B$, where z is given by $z = \sum_{j=1}^{n} s_j 2^{j-1}$ and $q_B(\Delta p)$ is the volume flow of the smallest ER valve. The usage of ER valves requires special attention to the dimensioning of the length L and the height H of the individual valves. For a proper operation of the digital ER valve it has to be guaranteed that the individual ER valves can be completely closed for the maximum expected pressure difference Δp_{max} if they are connected to the supply voltage U_{max}. This leads to the condition $\Delta p_{max} \leq 2L\tau_0(E_{max})/H$ with $E_{max} = U_{max}/H$ for the choice of L and H.

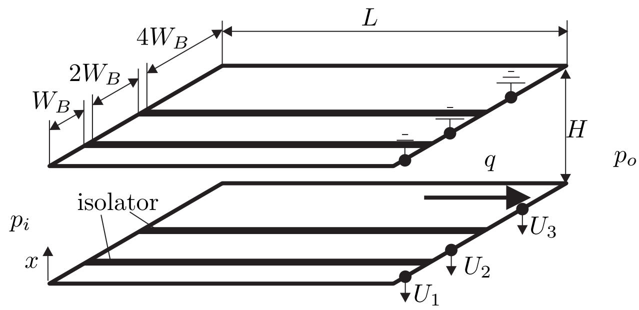

Fig. 5. Configuration of a 3 bit parallel digital ER valve.

Figure shows the pressure-volume flow relationship for a digital ER valve comprising 3 ER valves connected in parallel of height $H = 0.75$ mm, length $L = 70$ mm and $W_B = 5.7$ mm. It can be seen that the volume flow q through the digital ER valve can be controlled by switching on and off the voltages U_j of the individual ER valves. The main advantages of a digital ER valve in comparison to digital hydraulics using conventional valves are: (i) The construction of the individual ER valves is very simple. Thus, it is easier to guarantee the necessary manufacturing accuracy. (ii) The individual ER valves can be included in one flat (or annular) channel by simply adjusting the areas of the electrodes. (iii) The dynamics of the ER valves are basically independent of the width W_j of the valves. The main drawback of a digital ER valve in comparison to a continuously adjustable ER valve of same height, length and equivalent width $W = \sum_{j=1}^{n} W_j$ is, however, that its full work space cannot be covered.

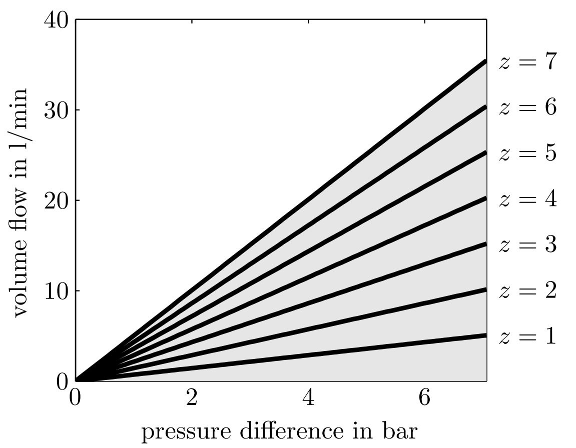

Fig. 6. Characteristics of a 3 bit parallel digital ER valve.

In many applications as e.g. semi-active dampers it is desired to control the pressure drop along the valve rather

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than the volume flow through the valve. Achieving this functionality with digital hydraulics based on conventional on/off valves is difficult. In contrast to conventional on/off valves, the pressure drop along a digitally controlled ER valve can be easily changed by switching on and off the applied voltage. Furthermore, the pressure drop along the ER valve for a constant voltage U and a constant volume flow q is a linear function of the length L of the valve. Thus, using n ER valves of height H, width W and length $L_j = L_B 2^{j-1}$, with the length L_B of the smallest valve, in a series connection, a digital ER valve can be constructed which is very well suited for the pressure control. The overall pressure drop along the serial digital ER valve is then given by $\Delta p = z\Delta p_B$, where z again is defined by $z = \sum_{j=1}^{n} s_j 2^{j-1}$ and Δp_B is the pressure drop along the smallest valve.

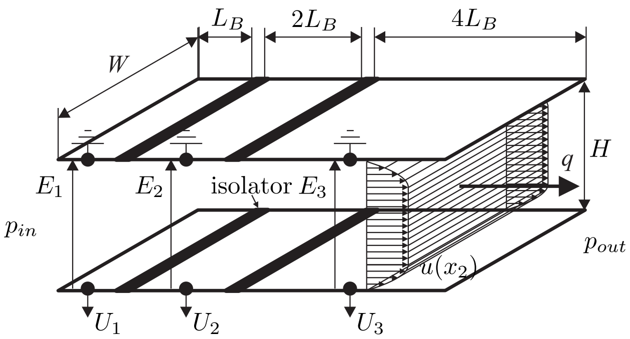

Fig. 7. Configuration of a 3 bit serial digital ER valve.

Fig. 7 shows a possible implementation of a serial digital ER valve with 3 bit. The corresponding pressure-volume flow characteristics of a valve with $H = 0.75$ mm, $W = 40$ mm and $L_B = 10$ mm is given in Fig. 8. This figure shows that a control of the pressure drop along the serial digital ER valve as a linear function of z is possible by switching on and off the voltage on the individual valves. The benefits of digital ER valves which use a series connection, can be summarized as follows: (i) In contrast to a parallel connection it is now possible to cover the whole operating range of a continuously adjustable ER valve. (ii) There is only a small dependence of the pressure drop along the digital ER valve on the volume flow through the ER valve. Thus, even large changes in the volume flow only lead to small errors in the pressure drop along the valve.

Up to now, a binary coding of the individual valves with size ratios of 2^{j-1} has been used, since this yields the lowest possible number of valves for a given resolution. However, since it is necessary to switch many valves at the same time in this coding scheme, e.g. when changing from state $z = 7$ to $z = 8$, unequal dynamics of the valves and non-ideal flow rates (e.g. due to manufacturing tolerances) might lead to pressure peaks and nonlinear characteristics. In order to circumvent these drawbacks different coding schemes have been outlined in the literature for conventional digital hydraulics. According to Linjama and Vilenius (2007), pulse number modulation with equal size of all valves has the best properties in this context whereas coding based on the Fibonacci numbers with ratios $1, 1, 2, 3, 5, 8, \ldots$ and other hybrid schemes represent

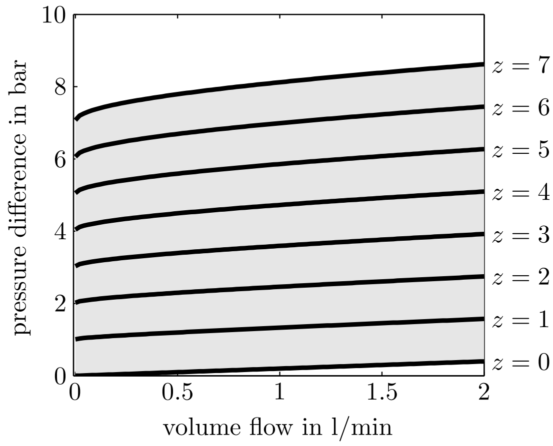

Fig. 8. Characteristics of a 3 bit serial digital ER valve.

a middle course. In any coding scheme the improvement of robustness is achieved by increasing the number of valves.

In general, the problems due to unequal valve rise times and non-ideal flow rates are much less serious when using ER-valves instead of conventional valves. As already mentioned, the construction of ER valves is very simple and hence a very accurate manufacturing can be expected. Second, the dynamics of ER-valves mainly depend on the oil density, oil viscosity and the height of the valve, see Kemmetmüller (2007). Thus, the dynamics is almost equal for parallel or serial connected ER valves of different length or width. However, if it is desired to use pulse number modulation due to its robustness, a large number of small and cheap valves is needed. ER valves are very well suited for this kind of applications, since a large number of valves can be easily designed by a suitable design of the electrodes of the valves. Despite the large number of valves, the construction and the electric control still remain simple and thus costs are expected to be low.

4. MEASUREMENTS

A test stand has been developed in order to show the feasibility of digitally controlled ER valves, cf. Fig. 9a. The test stand has two main features: (i) In addition to the measurement of the pressure drop, the volume flow, the voltage and the temperature, it is of great interest to examine the flow pattern within the ER valve. This requirement led to the use of optical transparent top and bottom walls (quartz glass) of the flat channel. By sputtering indium-tin-oxide (ITO) onto the glass surface, highly conductible electrodes of almost arbitrary shape and with a high optical transmittance are produced. Fig. 9b depicts the upper and lower electrode of a 3 bit serial digital ER valve. (ii) It is desired to test different configurations of serial or parallel digital ER valves with different shaping of the electrodes. This can be easily achieved by changing the two glass disc with the electrodes sputtered on.

In the subsequent measurements a 3 bit serial digital ER valve as depicted in Fig. 7 and Fig. 9b with a height $H = 0.75$ mm, a width $W = 40$ mm and a length $L_B = 10$ mm is considered. For the validation of the 3 bit serial digital ER valve static and dynamic measurements were carried out. The measured (static) pressure-volume

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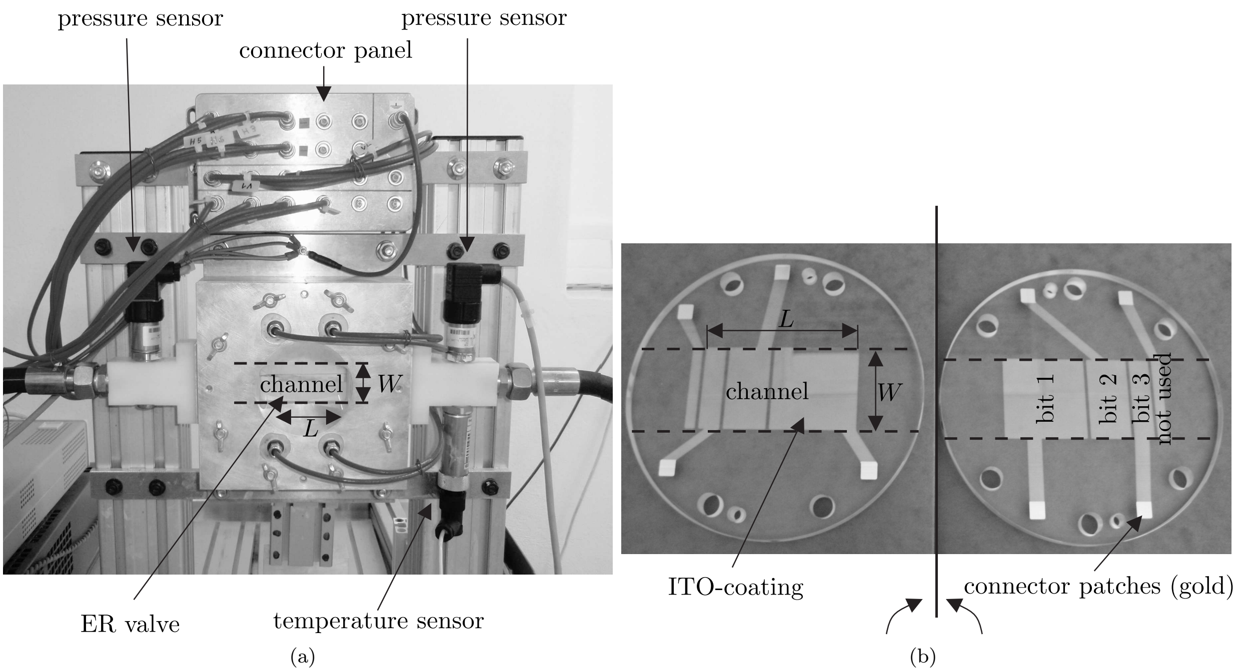

Fig. 9. (a) Optical ER valve test stand and (b) ITO coated glass discs.

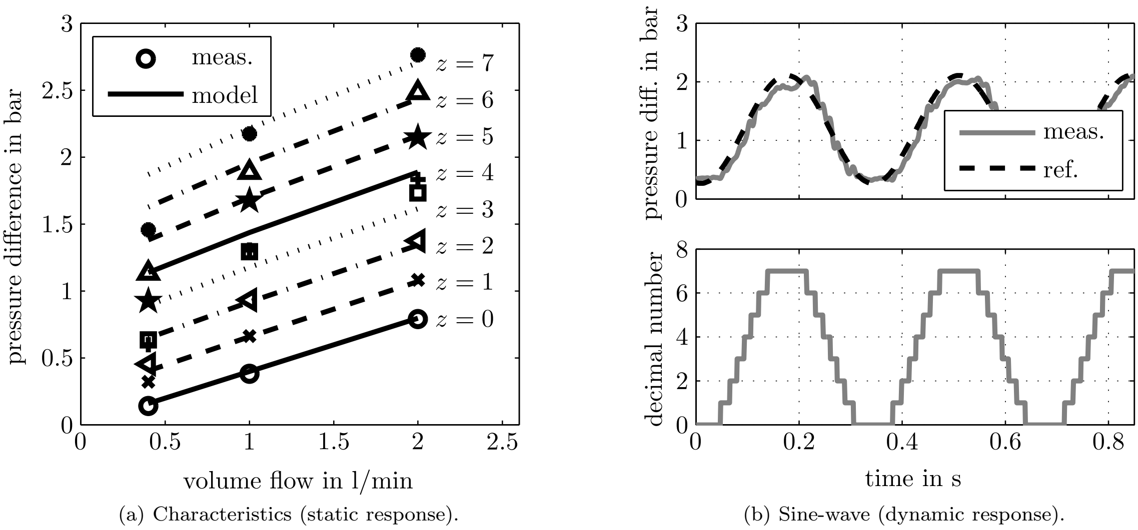

Fig. 10. Comparison of measurement and calculation of a 3 bit coded cross structured ER valve.

flow characteristics reveal good agreement with the mathematical model for moderate and high volume flows, see Fig. 10a. In the case of very low volume flows, however, larger deviations occur. This is due to the fact that the considered constitutive equation (1) is incapable to exactly describe the behavior for small shear rates $\dot{\gamma}$. In practical application it is possible to avoid very low shear rates by means of a suitable construction of the valve. Furthermore, the static behavior can by approximated by look-up tables or more complex material models which are based on the measurement results. Nevertheless, the basic functionality of the serial digital ER valve could be demonstrated by the static measurement results.

To show the dynamic behavior of the serial digital ER valve a sinusoidal pressure signal is tracked with the digital ER valve at a constant volume flow of $q = 2$ l/min. The results in Fig. 10b show again very good agreement of the measurements with the expected behavior. Especially, no pressure peaks during the switching of the valves could be observed which was of course expected from the theoretical examinations.

5. CONCLUSION

In this contribution the idea of digital hydraulics was successfully adapted to ER valves. Thereby, it could be shown that a parallel connection of ER valves yields a

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good control of the volume flow while a serial connection of the individual ER valves permits the exact control of the pressure drop along the valve. Measurement results of a 3 bit serial digital ER valve on a test stand confirmed the results of the theoretical examinations and proved the feasibility of the proposed digital ER valves. System inherent problems often occurring in conventional digital hydraulic systems as e.g. pressure peaks and step size uncertainties, could be kept very small in the proposed digital ER valves. As already mentioned, the intended application of such a digital ER valve are semi-active ER dampers which can be used e.g. in automotive systems. Further research will therefore focus on the implementation of digital ER valves in semi-active damping systems. A possible first schematic construction of a semi-active damper comprising a 3 bit serial digital ER valve is given in Fig.11

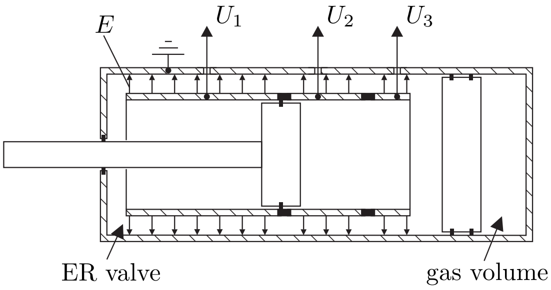

Fig. 11. Proposed contruction of a digitally controlled semi-active ER damper with a 3 bit serial digital ER valve.

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