Design Concept for the Development of Cylinder Drives based on Electrorheological Fluids

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ABSTRACT: This article deals with the practical use of electrorheological fluids (ERFs). At the Institute for Fluid Power Drives and Control (IFAS), a test rig has already been in use for several years and different applications have been investigated with it. During these investigations, information about the various influences on the ER effect, in terms of yield stress and current density, could be gathered. Due to the improvement of the ERF itself and the associated components, it is now possible to build up cylinder drives with improved forces and dynamic behavior. Nevertheless, there is still a lack of design rules and design aids for applications based on ERFs till today. After introducing some of the applications developed at IFAS, this article presents the latest measurements of valves based on ERFs. Knowing the influence of geometric parameters on the ER effect, a mathematical model has been adapted to the fluid used in recent measurements. It is also shown that a modular design of the cylinder drives makes the setup of the simulation model possible and enables the application engineer to carry out an accurate measurement.

Key Words: ERF, electrorheological, cylinder drive, electrorheological valve, step response, simulation, design, flow-mode.

INTRODUCTION

ELECTRORHEOLOGICAL fluids (ERFs) have been examined for more than 50 years now. While fluids are being improved continuously, many applications have been found based on these kinds of controllable fluids. This was accomplished in a similar way for magnetorheological fluids (MRFs). Due to the constitutive differences between the two fluids, some applications are more appropriate for one fluid, and others more for another. At IFAS several applications based on ERF were examined. The focus of these investigations is on the ER-valve, a capillary gap where the ERF is led through. Most of the used ER-valves consist of an annular gap, although measurements of rectangular gaps have also been carried out. Such an annular gap is shown in Figure 1. The most obvious advantage of ERFs is its high dynamic response behavior. Moreover, it has been shown that ER-valves show faster response time than MR-valves (Choi and Wereley, 2002). Therefore, investigations at IFAS are focused on applications that require an improvement of the dynamic behavior.

APPLICATIONS

Using ER-valves in a servohydraulic bridge a circuit can be built up, which normally consists of proportional valves. If an improvement of the dynamic behavior is required, exceeding the dynamics of conventional components, ER-valves should be considered. One example is to use ER-valves as the pilot stage in a two-stage valve with high nominal volume flow. Figure 2 shows the hydraulic circuit diagram of such a pilot-driven valve with a nominal flow of 160 L/min (NG16). It consists of two (adjustable) constant resistors upstream the main spool and two electronically controlled ER-valves downstream. Using this design the dynamic behavior of the valve can be improved (Zaun, 2004a).

The most detailed investigations were conducted for cylinder drives based on ERF. The prevalent control concept uses a so-called A + A circuit with four variable resistors. Unlike the conventional system with a valve consisting of four control edges, every single resistor can be adjusted separately. A cylinder drive with such a control system has been investigated at IFAS. It exhibited an excitation frequency of 400 Hz using a closed-loop position control (Fees, 2001). The dynamic limitation was given by the hydraulic as well as the electric components. The ER-valves as well as the mechanical system of the cylinder drive have the capability for a higher dynamic behavior. For further information about this cylinder drive see the work by Fees (2003).

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RECENT MEASUREMENTS

Owing to the continuous improvement of the ERF and its associated components, as high-voltage amplifiers, basic measurements have to be repeated in order to go along with this continuous development. The fluid used in recent measurements is RheOil 2.0 distributed by Fludicon GmbH/Darmstadt. These measurements were carried out with different valve geometries in order to evaluate the influence of geometrical parameters such as valve length, height, and mean diameter. Using these measurements, the influence of valve length on the response behavior has been investigated. Figure 3 shows the step response of two valves with different valve lengths. The length of the ER gap in Valve 213 is 300 mm, whereas the length of Valve 211 is only 100 mm. Within the first millisecond the pressure difference along the ER Valve 213 rises with a speed of 16.4 bar/ms, whereas the pressure difference at Valve 211 rises with a speed of 9.2 bar/ms.

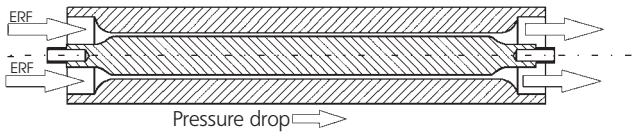

Figure 1. *A sectional view of an annular ER-valve.*

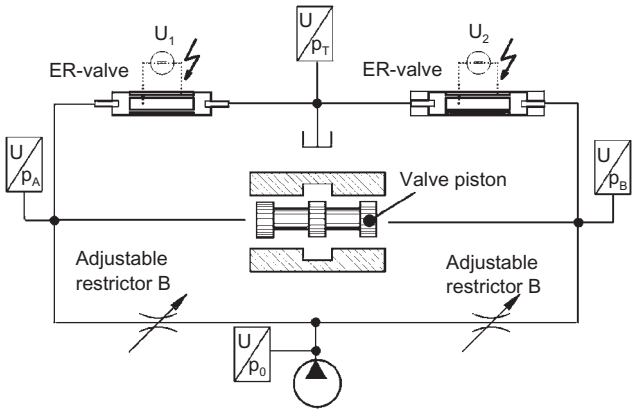

Figure 2. *Design of a ER-based pilot valve.*

Typically the length linearly influences the time constant of hydraulic components like pipes. This correlation is expressed by the hydraulic inductance:

$$L_{\mathrm{H}} = \frac{\Delta p}{\dot{Q}} = \frac{l \cdot \rho}{A}. \tag{1}$$

Therefore an increase of pipe length would slow the system behavior. From Figure 3 it can be seen that an increase in length increases the reachable pressure difference but does not influence the response behavior according to Equation (1). A change in gap height affects the dynamic behavior in a manner opposite to that defined in Equation (1). According to Equation (1), an increase in the gap height and thereby an increase in the cross-sectional area A effects a decreasing hydraulic inductance. Figure 4 shows the step response for three

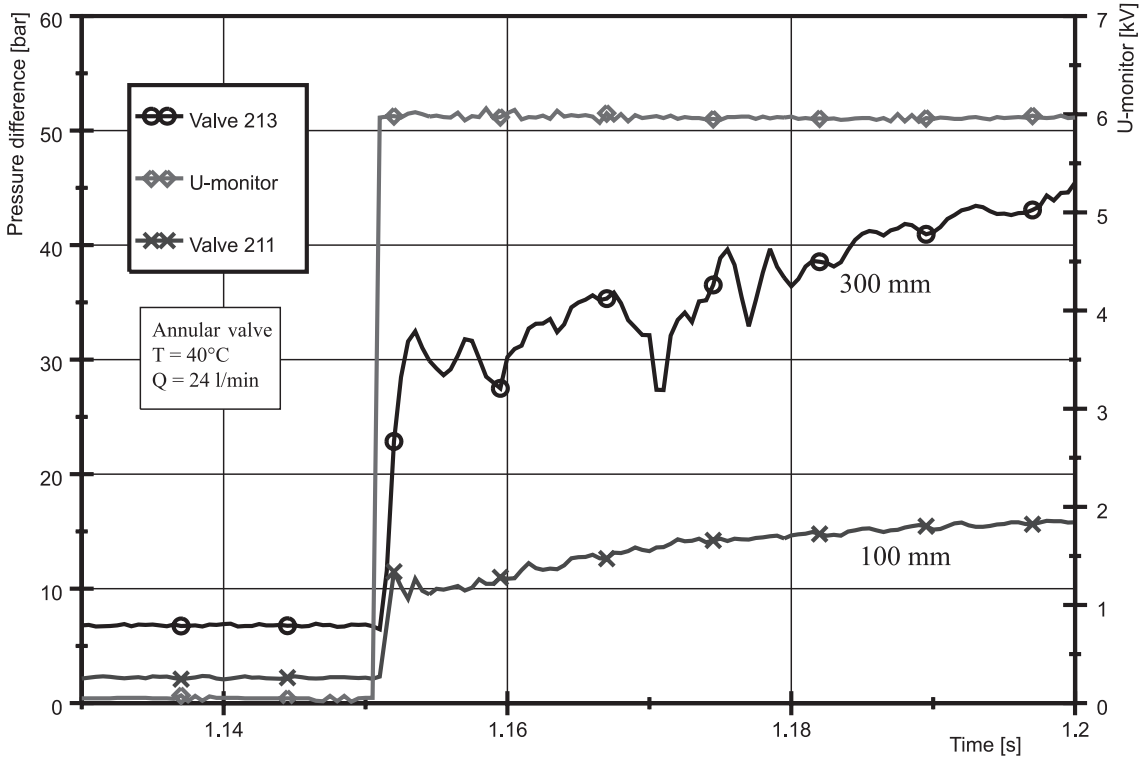

Figure 3. *Step response of two ER-valves with different valve lengths ($l_{213} = 300$ mm, $l_{211} = 100$ mm).*

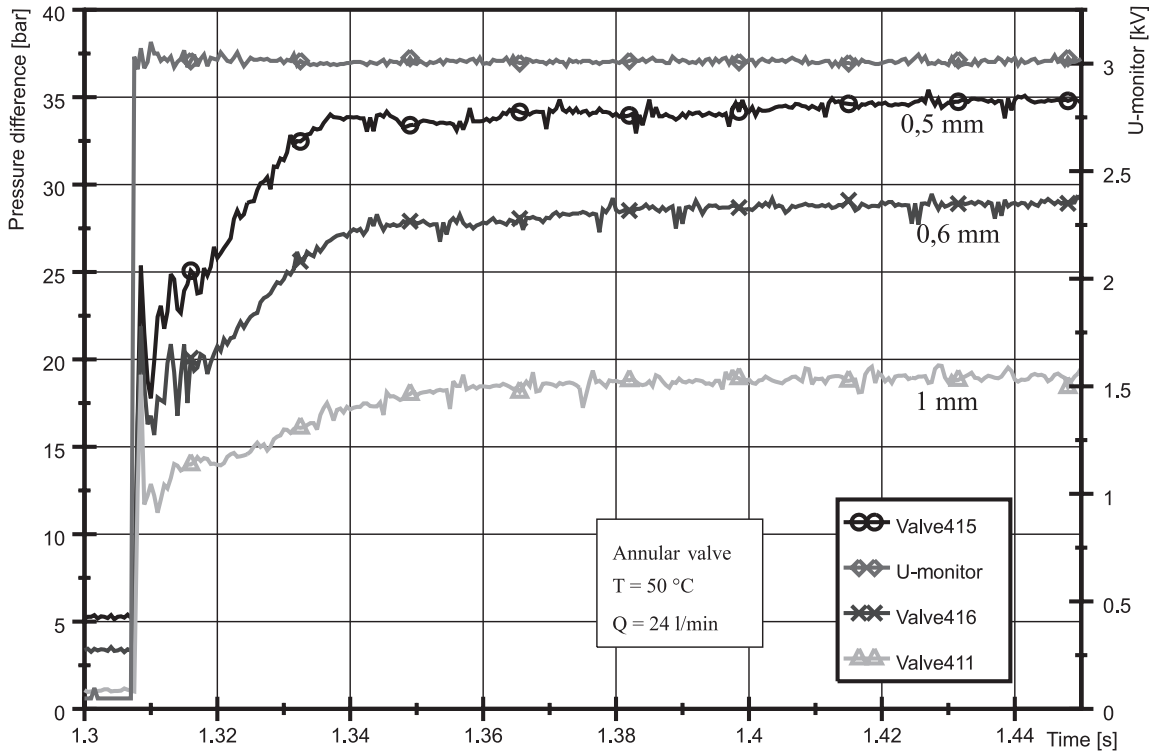

Figure 4. *Step response behavior of three ER-valves with different gap heights ($h_{415} = 0.5$ mm; $h_{416} = 0.6$ mm; $h_{411} = 1$ mm).*

valves with different gap heights. The first step response within <1 ms is out of the resolution of the pressure sensor, but the further development of the pressure difference shows a faster response time for a smaller gap height.

Besides the yield stress in terms of the pressure difference, another characteristic value has been focused on. The current density J is the value of the electric energy required for an ER-valve to reach the desired pressure difference and the desired yield stress respectively. Knowing the influence of temperature and flow rate, appropriate applications can be built that provide a high efficiency in terms of high yield stress and low current density.

MATHEMATICAL MODEL

Based on a mathematical model developed at IFAS (Wolff-Jesse and Fees, 1998), a simulation model has been implemented. The mathematical model is a phenomenological model that allows one to approximate the dependency of yield stress τ_E on field strength, gap height, gap length, and flow velocity.

$$\tau_E = (E, E^2, E^3, h, h^2, l, l^2, v). \tag{2}$$

This model contains 36 coefficients, which have to be determined for every fluid. Due to the significant improvement of the fluid RheOil within the last years, the coefficients have been redetermined recently to fit the behavior of the current fluid. With these coefficients the model was implemented in the standard software tool DSH*plus* for the simulation of hydraulic networks. After calculating τ_E the respective ER pressure difference will be calculated within DSH*plus* according to the following common equation:

$$\Delta p_E = 2 \cdot \frac{l}{h} \cdot \tau_E. \tag{3}$$

The model is restricted due to the limitation of measurements that determine the coefficients. Nevertheless, the model has been validated for measurements within the boundaries shown in Table 1.

Table 1. Boundary for the existing simulation model.

Field strength	$E = 0$–6 kV/mm
Mean flow velocity	$v = 0$–5.3 m/s
ER gap height	$h = 0.5$–1.3 mm
ER mean diameter	$D = 20$–40 mm
ER gap length	$l = 100$–300 mm

DESIGN CONCEPT

Based on the knowledge gained regarding the dependencies of yield stress τ_E and current density J,

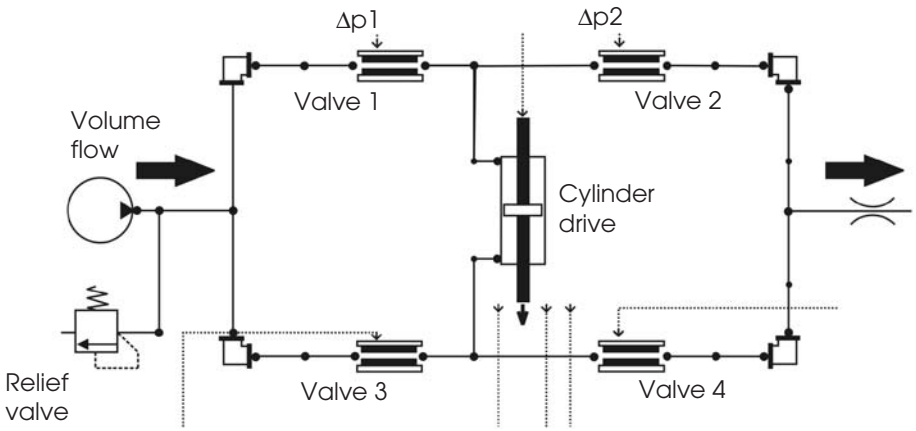

Figure 5. *Hydraulic circuit of a servo cylinder drive with four ER-valves.*

a design concept has been developed in cooperation with FLUDICON GmbH/Darmstadt to improve and accelerate the design process of ER cylinder drives. This design concept consists of the following steps:

(1) Determination of the constraints.
(2) Calculation of general data of the ER-valves and the cylinder drive.
(3) Design of the hydraulic circuit and detailed design of one valve module.
(4) Manufacturing of one ER-valve module.
(5) Simulation of the system as a whole.
(6) Measurement of the ER-valve.
(7) Extension of the mathematical model.
(8) Design and simulation of the closed loop control.
(9) Manufacturing of the cylinder drive.

The first step is the generation of a product specification sheet. With these specifications, general calculations can be conducted in the next step. Two basic equations help to find the needed geometric parameters. The first one is the electrical energy balance. From the available electrical power of the voltage amplifier and the current density, a maximum electrode surface can be obtained. The unknown value is the voltage that depends only on the gap height. The field strength required to reach a maximum ER-effect is typically the limit due to an electrical breakdown, the dielectric strength:

$$P_{\text{electrical}} = U \cdot I = E \cdot h \cdot J \cdot \pi \cdot D \cdot l. \tag{4}$$

The second equation is related to the hydraulic energy balance. The hydraulic power is given by the maximum volume flow $Q_{\max}$ and the maximum pressure difference $\Delta p_{\max}$. The maximum pressure occurs when the piston starts from an end position because in this position the maximum acceleration is required. Valve 2 is closed and Valve 1 remains fully open if the piston reaches the top end position, for example. The piston does not move yet. Hence half of the maximum volume flow flows along both the valves because the hydraulic resistance along the valve bridge is symmetrical (Figure 5).

Hence the maximum hydraulic power is

$$P_{\text{hydraulic}} = \frac{Q}{2} \cdot (\Delta p_{\text{E}} + 2 \cdot \Delta p_0) \tag{5}$$

with Δp_{E} as the pressure difference that can be engaged due to controllable electrical field (ER pressure difference) and Δp_0 as the pressure difference due to the newtonian viscosity, which represents the inevitable power loss. From Equation (3), Δp_0, and Hagen–Poiseulles' law a ratio of mean diameter and length can be expressed as follows:

$$\frac{D}{l} = \frac{12 \cdot Q \cdot \eta}{\pi \cdot h^3 \cdot \Delta p_0}. \tag{6}$$

Using Equations (3), (4), and (6) the yield stress can be calculated depending on the gap height, which is also related to the voltage and the flow velocity. The voltage increases with increasing gap height in order to keep the field strength constant and the mean flow velocity decreases with increasing gap height. With this mathematical correlation an optimization of the geometric parameters can be accomplished. With these geometric parameters of the valve the piston area, piston rod diameter, and the maximum weight of the piston and piston rod can be calculated in a similar manner. Restrictions are the available Δp_{E}, required working force of the cylinder drive, stroke, acceleration, and volume flow. With a developed design recommendation (Zaun, 2004b), a valve module will be designed in a third step, which can be measured without the cylinder drive as a whole. Parallel to the manufacturing of this valve module (fourth step) a simulation model will be built that contains all the design parameters known. With this model a simulation in the fifth step helps to evaluate the expected valve and system behavior. With measurements of the valve module in the sixth step, the valve behavior can be validated and due to the approved

simulation software the whole system behavior will also be validated. If necessary the boundaries (e.g., the mean flow velocity) of the simulation model can be extended with measurements in the seventh step, using the valve module. In the eighth step, a closed loop control strategy can be developed and tested within the simulation model. After processing the explained design steps, the behavior of the cylinder drive as a whole can be estimated, before manufacturing the system in the last step.

CONCLUSIONS

Owing to further developments in the field of fluids and associated components, the capability of ER applications increases. At IFAS, several investigations of annular ER-valves have been performed in order to support these developments and adapt a mathematical model. Because of these measurements data on the influences of parameters, such as valve length, height, mean diameter, flow rate, temperature, and field strength were obtained. A design concept is provided that improves and accelerates the design of high-capacity servo cylinder drives. This design concept contains recommendations for a modularization of such a system and the opportunity to simulate the whole system behavior including the closed loop control.

REFERENCES

Choi, Y.T. and Wereley, N.M. 2002. "Comparative Analysis of the Time Response of Electrorheological and Magnetorheological Dampers Using Nondimensional Parameters," *Journal of Intelligent Material Systems and Structures*, 13(7/8):443–452.

Fees, G. 2001. "Study of the Static and Dynamic Properties of a Highly Dynamic ER Servo Drive," *Journal 'O+P Ölhydraulik und Pneumatik'*, 45(1):112–120.

Fees, G. 2003. "High Dynamic Servo Drive for Hydraulic Applications," PhD Thesis, University-Aachen, Institute for Fluid Power Drives and Control.

Wolff-Jesse, C. and Fees, G. 1998. "Examination of Flow Behaviour of Electrorheological Fluids in the Flow Mode," *Proceedings of the Institute of Mechanical Engineers, Journal of Systems and Control Engineering*, 212:159–173.

Zaun, M. 2004a. "Trends in Electrorheological Valve Development," In: *Proceedings of the 4th International Fluidpower Conference in Dresden/Germany*, pp. 533–544.

Zaun, M. 2004b. "Measurements and Simulation of Electrorheological Valves," *Journal 'O+P Ölhydraulik und Pneumatik'*, 48(7):445–449.