DESIGN OF CYLINDER DRIVES BASED ON ELECTRORHEOLOGICAL FLUIDS

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Abstract

Short response times make electrorheological fluids (ERF) particularly suitable for the control of high dynamic applications. This paper deals with the usability of these controllable fluids and furthermore with the essential components to build up electrorheological cylinder drives. Hands-on experiences are explained in order to support the design of such systems. A design concept developed at IFAS has been applied to a new cylinder drive. The concept considers a total modularisation of the drive and the electrorheological valves. This paper demonstrates the advantages of this concept when using ERF.

Keywords: electrorheological fluid, response time, design concept, power supply, electrorheological properties, yield stress, cylinder drives, dynamic applications, modularisation, valve design

1 Introduction

Electrorheolocial fluids (ERF) change their rheological properties when exposed to an electrical field. The apparent viscosity increases rapidly with increasing field strength. Several applications based on ERF have been developed (Agrawal *et al.*, 2001) and electrorheological valves are one of them. ER valves consist of a capillary gap which is formed by two electrodes. Due to a pressure difference the ERF flows through the gap. Upon applying a strong electrical field the flow resistance increases substantially. Depending on the operating conditions the gap can be closed completely (Zaun, 2004a). There is still a lack of knowledge about the involved physical mechanism although this effect has been subject of research since W. Winslow 1947 carried out first experiments on it. Nevertheless the mathematical models based on the characteristics of the fluid materials and the operating conditions don’t describe the effect sufficiently yet. Hence empirical and phenomenological models and specifications are the tools for dimensioning applications.

The very short response time of ERF suggests the use in high dynamic applications. One example is the control of fast cylinder drives (Wei *et al.*, 2004). Different cylinder drives have been built up and measured at IFAS, RWTH Aachen University. With one of these actuators a closed loop control frequency of 400 Hz has been reached. Open loop control frequencies of more than 1000 Hz have been transmitted (Fees, 2001).

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If using ERF certain factors are very important for the success of a dynamic application. These factors are the fluid, the power supply unit, the design of the cylinder drive and the concept of the closed loop control.

2 Electrorheological Fluid

Today‘s available fluids consist of electrically polarizable particles suspended in a non-conducting fluid. The size of the particles ranges between 0.05 and 15 µm and the volume fraction between 30 and 50 %. Although there is a lack of understanding about the physical mechanism of the ER effect some facts are commonly accepted. Due to an applied electrical field the particles polarize and start interacting. This interaction can be enforced with the help of activators. In earlier works water has been used for this purpose.

At IFAS the ERF RheOil is mainly used. This commercially available fluid is distributed by FLUDICON GmbH/Darmstadt. RheOil is water free. It consists of polyurethane doped with a metal salt suspended in a silicon oil.

If the volume flow of an ERF ceases and the suspension remains under the influence of the electrical field the particles start to form microscopic structures.

Such chain-like or column-like structures have been observed in many cases (Wen *et al.*, 2003; Klingenberg and Zukoski, 1990; Conrad *et al.*, 1990). But even after the destruction of all structures in the fluid, for example by shearing of the fluid, an increase of the ER effect with an increasing electrical field is observed (Klingenberg and Zukoski, 1990). Hence not only the structures are responsible for the increase of the flow resistance. Electrophoresis is another effect observed with the ER effect. Charged particles tend to move towards one electrode. Regarding the use of ER valves it is accepted that this effect is negligible due to the high flow velocities. The flow forces cause a continuous exchange of the particles in the capillary gap. The following properties determine the quality of an ERF:

- electrorheological yield stress
- current density
- response time
- no-field viscosity
- density
- sedimentation tendency
- hysteresis
- temperature dependency
- abrasiveness
- compatibility with other hydraulic components (seals etc.)

Under the influence of an electric field a specific shear stress has to be exceeded to allow fluid flow. This threshold is the ER yield stress. Considering an ER valve the controllable pressure difference depends on this yield stress. In the case of a closed ER valve, the ER yield stress can be obtained from the balance of forces:

$$\Delta p \cdot b \cdot h = 2 \cdot l \cdot b \cdot \tau_{\mathrm{E}} \tag{1}$$

The valve characteristic is determined by the geometrical values gap width b, gap length l and gap height h of capillary gap. Δp is the difference of the pressures up- and downstream of the valve, whereas τ_{E} is the shear stress due to the electrical field. In the case of a volume flow through the ER valve, the relationship of the pressure difference and the field dependent shear stress depends on the flow profile and thereby on the physical mechanism of the ER effect itself. The relations between pressure, volume flow and ER-shear stress have been described before by models based on those of non-newtonian fluids. None of them is able to describe the fluid behaviour for different operation conditions sufficiently. For the successful determination of the yield stress in case of volume flow usually phenomenological models are used.

The current density can be calculated from the current consumption and the electrode area. It determines the electrical power loss of the fluid. Hence the electrode area is limited by electrical voltage, current density and by the available electrical power. The electrode area also affects the controllable pressure difference.

The reason to use ERF in any hydraulic system is the very short response time. However, different fluids exhibit conspicuously different response times. Therefore the ER shear stress and the current density together with the response time are some of the most important properties. Figure 1 shows the pressure difference across an ER valve as a response of the activated electric field. Two different ERF have been used in an ER valve with an annular gap. The gap height of the valve is 0.5 mm, the length 100 mm and the mean diameter 40 mm. Regarding RheOil 2.0 the first pressure step from around $6 \cdot 10^5$ Pa up to $20 \cdot 10^5$ Pa occurs within less than 1 ms.

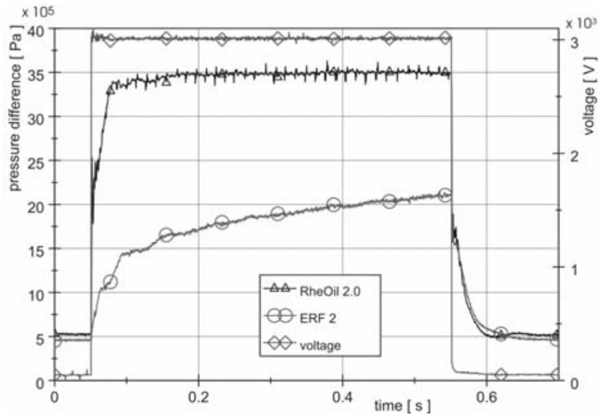

Fig. 1: *Step response of two different ERF*

The no-field viscosity is a cause of power loss in the same way as the current density. Without a field the ERF behaves almost as a newtonian fluid. As the ER gap can be assumed as a throttle, the hydraulic power loss increases linearly with an increasing volume flow and depends on the viscosity. Thus a low no-field viscosity is desired. On the other hand the viscosity has to be kept within the boundaries given by the hydraulic components. Pumps for instance typically require a kinematic viscosity between $10 \cdot 10^{-6}$ m²/s and $100 \cdot 10^{-6}$ m²/s. Recently a new ERF has been developed that exhibits extremely high yield stresses. Due to the boundaries of most applications (e.g. cylinder drives) this fluid is inapplicable because in the relevant temperature range the no-field viscosity is exceedingly high (Wen *et al.*, 2003).

The influence of the ERF density on the dynamics of the pressure generation is linear. The change rate of the volume flow in ER gaps can be described with Eq. (2) and it can be seen how the density ρ connects pressure and dynamical volume flow (Murrenhoff, 2001):

$$\dot{Q} = \frac{A_{\mathrm{spalt}}}{l \cdot \rho} \cdot \Delta p \tag{2}$$

The moderate density is one of the advantages compared to magnetorheological fluids, whose densities are 2-4 times bigger than those of ERF.

Sedimentation denotes the settlement of particles suspended in fluids due to gravity or other forces such as centrifugal force. In ER applications this issue has to be considered as with all other suspensions. The movement of the particles produces an inhomogeneity of the fluid, i.e. parts of the ERF are depleted of particles. If the particles are retained in the reservoir the ER shear stresses decrease. This can be detected by monitoring the viscosity. Additionally, settled particles can cause problems if they form a thick sediment. Some fluids exhibit a sediment that cannot be re-dispersed easily. Therefore the stability of the ER suspension is one of the factors of quality and is thereby a focus in ongoing investigations. The low density difference of particles and carrier fluid promotes the stability of the suspension significantly. Other beneficial attributes are to be seen in small sized particles, large volume fractions of the particles and high viscosity of the dispersants. The build-up of agglomerates due to Van-der-Waal forces degrades the stability. If the agglomeration is a loose network it can be re-dispersed easily. Viewing the current state of knowledge the sedimentation of a suspension cannot be avoided totally if the suspension is expected to behave as a newtonian fluid in the initial state. The density difference of particles and fluid can be reduced so far that the interparticle forces and the brownian-motion forces are in balance (Dörfler, 1994). In that case sedimentation stops completely. Owing to the temperature dependency this balance can be kept only at one temperature.

The characteristic of the pressure difference in case of increasing field strength compared to decreasing field exhibits a variance. This hysteresis makes closed loop control difficult. Therefore a small hysteresis is strictly desired. The voltage gradient as well as the mean flow velocity and the temperature have been identified as influence factors. Figure 2 shows three measurements with the same ERF and valve. The voltage has been increased over 5 s up to around 6000 V. Afterwards it has been decreased over the same period. At the same voltage the pressure difference exhibits a higher value in the case of decreasing voltage. At a temperature of 50°C and a flow rate of 8 l/min the hysteresis is negligible. Dropping the temperature to 30°C the difference between increasing and decreasing the voltage rises up to a maximum of $1 \cdot 10^5$ Pa. As it can be obtained from Fig. 2 the hysteresis can be reduced significantly by increasing the flow rate. The drop of the maximum pressure difference comes from the negative dependency of the ER yield stress on the flow rate.

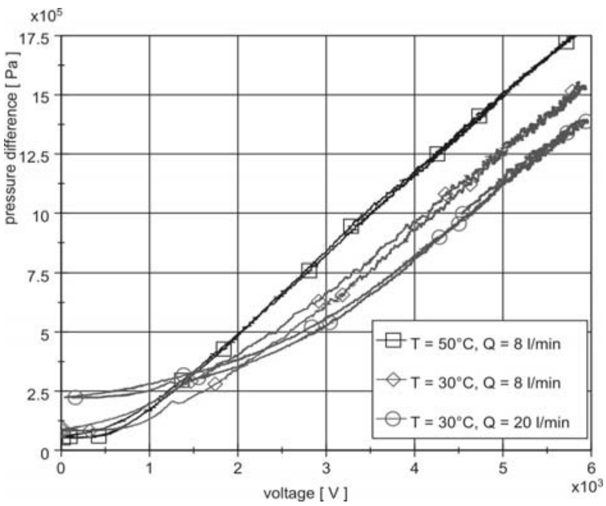

Fig. 2: *Hysteresis under different operating conditions*

The temperature has significant influence on several characteristics, such as that of the yield stress, the current density, response time and hysteresis as mentioned above. Starting from room temperature, the yield stress increases with increasing temperature up to a maximum and drops thereafter. The current density increases with temperature continuously, whereas the hysteresis decreases with increasing temperature. Nevertheless an influence of the temperature is not wanted and a constant characteristic of all properties over a wide temperature range is desired. Figure 3 shows the dependency of ER yield stress and current density on the temperature. The dimensions of the ER valve are the same as in the measurement illustrated in Fig. 1

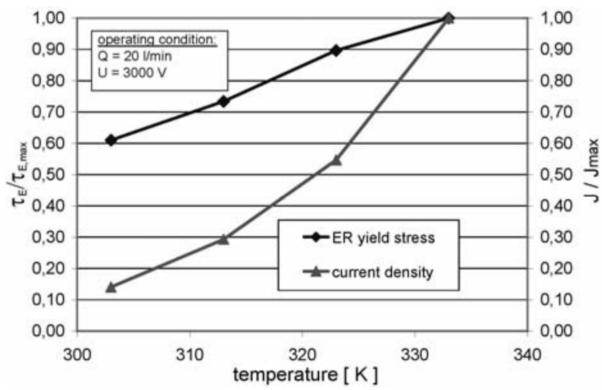

Fig. 3: *Temperature dependency of RheOil 2.0 regarding ER yield stress and current density*

In the use of ERF, abrasion was a problem for a long time. However some modern-day ERF show no measurable abrasive effects on conventional components over a long operation period. This, along with a good chemical compatibility with the components, such as seals, is in common demand and ERF are available that meet this requirement.

Table 1 shows some fluid data of RheOil 2.0. As explained above, the ER yield stress depends on several parameters, such as temperature, shear rate/flow rate, available electric power etc. Therefore a general maximum ER yield stress cannot be given.

Table 1: Characteristic values of RheOil 2.0 (NN, 2002)

zero field viscosity (25°C, 1 bar)	0.05 Pa·s
volume fraction of the particles	50%
density	1040 kg/m³
operating temperature range	-40 - +120 °C

3 Electrical Power Supply

A system based on ERF requires an electrical power supply that provides sufficient voltage and current with much shorter response time than the ERF in order to benefit from the high dynamic ER effect. Power supplies can be classified according to their capability of being discharged actively or passively and capability of delivering positive and/or negative voltages. For details about properties of different power supplies for ER applications see (Rech, 1996). At IFAS a DC device from FLUDICON GmbH is used. It can be discharged actively (two quadrants). The –3dB cut-off frequency is more than 3 kHz. With the power of 120 W voltages of 6 kV can be generated. Important for the security of the user and the application is the automatic shut-down in case of a short circuit or an overload. This feature helps to prevent damage to components due to the short circuit if the ERF gets contaminated e.g. with water.

4 ER valve

ER valves consist of two electrodes. The gap between these electrodes allows a nearly homogenous electric field to be activated and ERF is channelled through. To come up to these demands the electrodes have to be kept at a constant distance and separated by an isolator that meets the requirements of a hydraulic system (e.g. pressure, temperature). The characteristic values of an ER valve are the geometric values as mentioned in Eq. (1). They determine the ER-properties. Through an appropriate design certain benefits of integration or modularity of the valves can be achieved. The choice of the design and of the characteristic values dominantly affects the manufacturing costs. Due to common gap heights of about 0.5 to 1.3 mm and lengths of more than 100 mm, high tolerances are required. Some examples of different valve designs and their integration into the structure of a cylinder drive are shown in Fig 4.

Figure 5 shows the typical hydraulic circuit design if ER valves are used to control a cylinder drive.

The simplest design is that of a rectangular gap (A) (see Fig. 4). In this case the electrodes are two plates separated by a very slim isolator. Centred along the width of the valve a clearance in this isolator provides flow path for the ERF. With an activated electrical field the flow resistance of this gap can be increased and under certain conditions the valve can be fully closed. Depending on the application such a design allows full integration. Whether an integration into the design of a cylinder drive makes sense or not depends on the particular application (B). The disadvantage of a rectangular gap is the large electrode surface subjected to high pressure. This could cause a widening of the gap and thereby a decreasing ER effect. Unlike rotational geometries large, accurately planed plates are expensive to manufacture. For this reason, annular gap geometries are very often preferred (C–G). In this case the valve consists of a round steel as the inner electrode and a tubular cylinder as the outer one. Mathematically the annular gap can be treated as a rectangular gap if the gap is imagined as winded off. The gap width then corresponds to the gap circumference. In this case the need for a precise and concentric positioning of the inner cylinder relative to the outer cylinder in order to maintain a constant gap height along the entire gap length must be observed. Considering the isolator between the two electrodes, long tolerance chains may be created. One single ER valve is less easy to integrate into the structure of a cylinder drive (D) than several smaller valves (E, F). Mathematically there is no difference between one annular gap and several parallel bridged gaps with the same effective gap width. The gap length is of great influence on the controllable pressure difference. The equation describing a throttle flow (Murrenhoff, 2001) considers the gap length only linearly, yet on the ER-shear stress it has a disproportionate effect (Zaun, 2004b). One reason is the fact that by extending the gap length while sustaining a constant flow rate, the duration of a particle passing the gap is increased. To benefit from this fact it can be useful to connect two or more ER valves sequentially (G). In order to achieve a compact design two ER gaps can be grouped side by side. ERF is directed through the first gap, reversed and led back in the opposite direction through the second gap. In this case the hydraulic losses due to the direction change of the fluid have to be considered. Furthermore the distance of each particle travelling between two gaps has to be minimised due to the relaxation of the particles outside the field. Another way of extending the gap length is an ER gap as shown in (H) in Fig. 4. A sealing cord is coiled between the inner and the outer electrode. The ERF flow follows the spiral flow channel, which prolongs the fluid's stay in the gap. However, this design slightly increases the hydraulic loss. Currently this design is used only within passive systems.

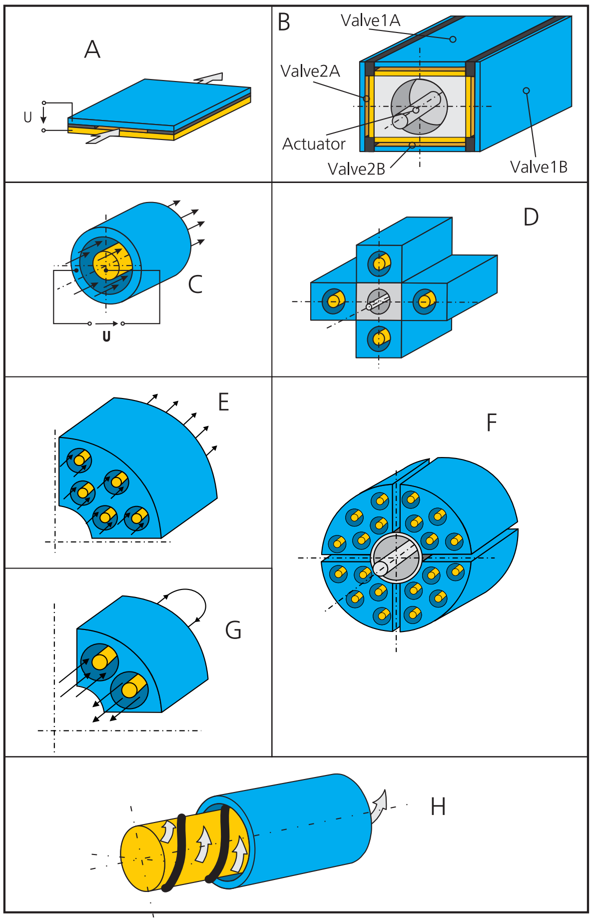

Fig. 4: *Overview of different valve designs*

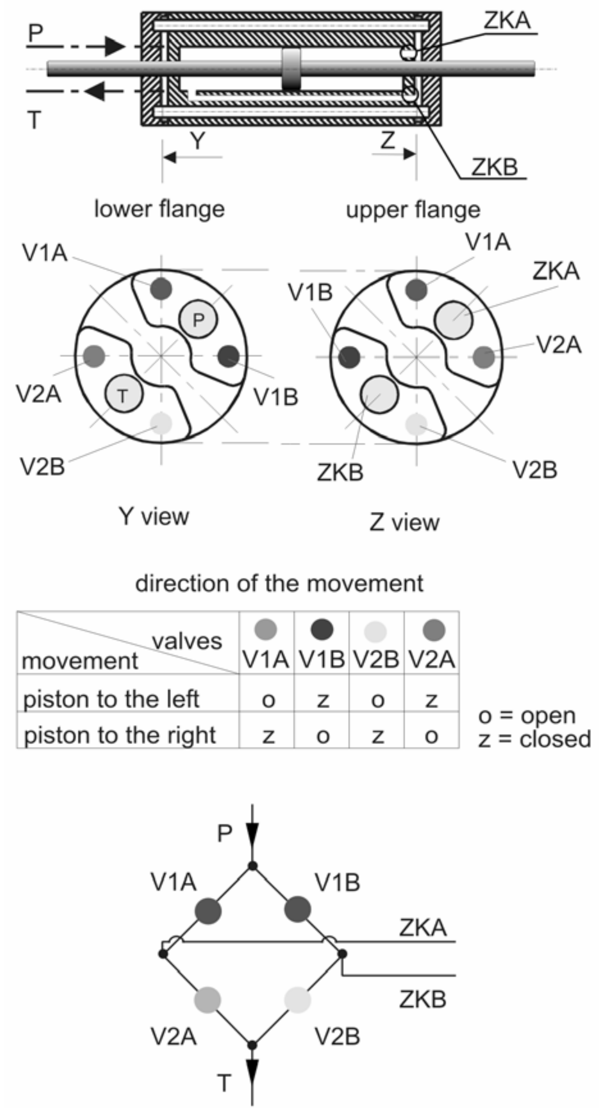

Fig. 5: *Circuit with 4 ER valves for the control of a cylinder drive (A+A servo bridge)*

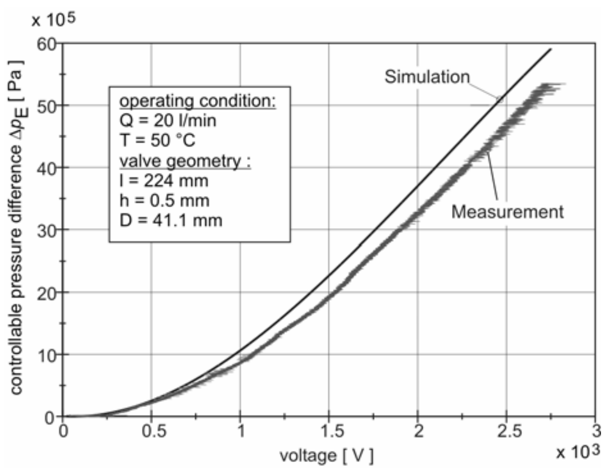

Fig. 6: *Measurement of the controllable pressure difference*

With a simulation tool that uses a phenomenological model of the flow behaviour, ER valves can be simulated within certain operating conditions (Fees, 2004; Wolf-Jesse and Fees, 1998; Zaun, 2004). Figure 6 shows a comparison of simulation and measurement regarding a valve module that has been dimensioned with the aid of this simulation tool. The valve follows the design of (E) and (G) in Fig. 4. Figure 7 shows the experimental setup.

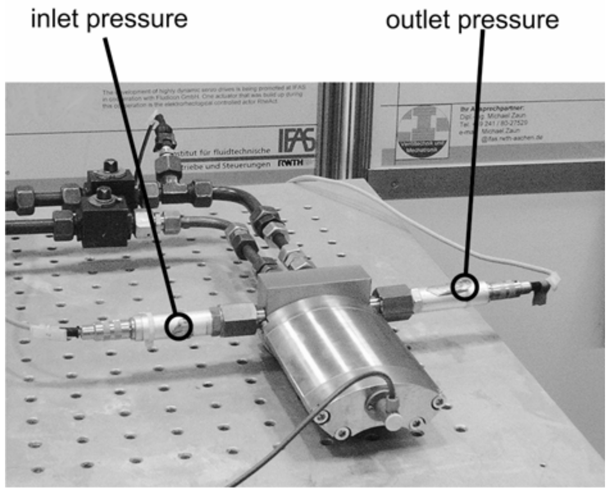

Fig. 7: *Measurement of the controllable pressure difference*

5 ER-Cylinder Drives

As a result of the absence of valid models for the description of the flow behaviour of ERF, there is a lack of design rules and dimensioning aids for the design of cylinder drives controlled by ER valves. The question arises how a valve can be dimensioned if a calculation of the controllable pressure differences is not possible. Therefore a design concept has been developed that structures and supports the design process (Zaun, 2004c). Measurements cannot be avoided entirely but they don't have to be focused on the whole cylinder drive. Only one valve module has to be measured in order to verify the simulation and extend the model if the operating condition exceeds the valid range of the model. By doing so, the behaviour of the cylinder drive is known before it is manufactured. For validation of this design concept a double rod cylinder drive has been designed which combines the knowledge gained with other cylinder drives developed at IFAS. The digital mock-up of this drive is shown in Fig. 8.

Table 2 presents some characteristic data.

Table 2: Data and characteristics of the cylinder drive

ER Cylinder Drive (IFAS)	
Nominal Force	1000 N
Stroke	+/- 35 mm
Desired Excitation Frequency	1000 Hz
Dimensions	∅ 200 x 360 (with piston rod)
Characteristics	Hydrostatic Bearing Cushioned Cylinder Strictly Modularised

Fig. 8: *Digital-Mock-Up of the new cylinder drive*

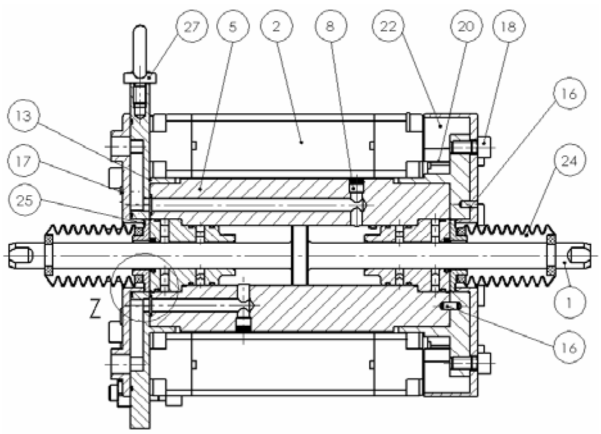

Fig. 9: *Drawing of the new ER cylinder drive*

Due to the degree of modularisation it is possible to transform the cylinder from double rod into single rod design only by exchanging three parts. If ERF is used to control a cylinder drive the available pressure differences are limited. Therefore it is essential to examine the effective piston area and the weight of all moving parts. A larger piston area does not raise the acceleration force because it increases also the hydraulic capacitance C_H. An increasing mass of piston and piston rod reduces the dynamics as can be seen in Eq. (3) and (4).

$$\ddot{x}_K \cdot m_{K,St} = A_K \cdot p_{eff} \tag{3}$$

$$\ddot{x}_K = \frac{1}{m_{K,St}} \cdot A_K \cdot \int \frac{1}{C_H} \cdot Q \mathrm{dt} \tag{4}$$

where

$$C_H = \frac{V_0 + A_K \cdot x_{max}}{E_{ERF}} \tag{5}$$

Hence lightweight construction offers the potential of higher dynamics for this kind of cylinder drives. Two examples of suitable aluminium alloys with sufficient properties for this application are AlZnMgCu0,5 and AlMgSi1. While an increasing piston surface does not affect the dynamic properties significantly, the static force rises when keeping the moving mass constant. The use of a differential cylinder drive offers a higher static force in one direction. The use of four valve modules in the control loop offers the possibility of designing each resistor of this bridge separately (see Fig. 5). Thus, the piston can be held in a resting piston in spite of the differential areas, while all valves receive the same excitation. This simplifies the control strategy. At IFAS a control strategy for ER-cylinder drives has been mapped out that is based on this fact. Hence it can be used for double rod cylinder drives as well as for differential design. Another control strategy takes advantage of four control variables for one desired value. This over-determined system is used within a flatness based control strategy (Kemmtmüller and Kugi, 2004). Both of the strategies have been applied to the control of the same cylinder drive with satisfying results. This cylinder drive has seals and guide bands which cause friction on the piston rod. Undesired hysteresis and friction forces are the consequences. The newly developed cylinder drive (Fig. 8) employs a special kind of hydrostatic bearing. The size of the feed bore and of the return bore must allow unimpeded passage of the particles.

Conclusions

The short response time of ERF can be used to control high dynamic cylinder drives. For the selection of a suitable ERF attention has to be focused on the characteristic properties. These properties have to be considered in order to design a capable system and benefit from the advantages of ERF. Today’s available power supplies offer the necessary dynamics for the excitation of ERF with high voltages and frequencies. The design of an ER valve allows an excellent integration into an application. However, up to now there is a lack of design and dimensioning tools due to the unknown physical mechanisms within the fluid. The knowledge and the experience gained in earlier approaches in the field of ERF have been collected in terms of a systematic way of developing an ER-cylinder drive. The proposed design concept has been applied in the design process of a new cylinder drive. This actuator uses the advantages of modularisation. The nominal force is 1000 N.

Future steps will include the measurement of the cylinder drive as a whole and the validation of the simulation results. The primary objective in this is to prove the anticipated excitation frequency of 1000 Hz.

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Nomenclature

A_{spalt}	cross-section of the valve gap	[m²]
A_K	effective piston surface area	[m²]
b	gap width of the valve	[m]
C_H	hydraulic capacitance	[m³/Pa]
D	mean annular diameter of the valve	[m]
E_{ERF}	effective bulk modulus	[Pa]
h	gap height of the valve	[m]
J	current density	[A/m²]
l	gap length of the valve	[m]
$m_{K,St}$	mass of piston and piston rod	[kg]
p_{eff}	effective pressure	[Pa]
$\dot{Q}$	change rate of the volume flow	[m³/s²]
x_{max}	piston stroke	[m]
$\ddot{x}_K$	acceleration of the piston	[m/s²]
V_0	dead volume	[m³]
Δp	pressures difference	[Pa]
η_0	initial dynamic viscosity in absence of a field	[Pa s]
ν	kinematic viscosity	[m²/s]
ρ	density	[kg/m³]
τ_E	electrorheological yield stress	[Pa]

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