

FACTORS INFLUENCING LOAD TRANSMISSION THROUGH ELECTRORHEOLOGICAL CYLINDER CLUTCH

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This paper discusses the influence of factors shaping electrorheological characteristics of a clutch. Dependencies on the torque transmitted by the output shaft of the clutch were determined for various rheological models. The main part of the work is devoted to rheological modeling of the electrorheological cylinder clutch. The discussed rheological models include: visco-plastic and visco-elasto-plastic Bingham models, visco-elasto-plastic Gamota-Filisco, and Li models. The research stand and possible tests are described. The remaining part of the work discusses electrorheological characteristics of the ER fluid. Moreover, directions for further research on the laboratory stand designed and made by the author were formulated.

Key words: rheological models, electrorheological cylinder clutch, electrorheological fluids, dynamic viscosity, test stand

1. Introduction

Developments in the material engineering have resulted in access to new materials and new possibilities related to their application in various machine designs and constructions. Electrorheological fluids have already been applied to a range of industrial goods. They are used in clutches, brakes, mechanical screwdrivers, elastic blocks, torsional dampers, shock absorbers, high voltage feeders, valves, changeable module beams, servo-mechanisms, and hydrokinetic torque converters.

Electrorheological fluids have been specifically studied and applied in the design and construction of machines only in the recent two decades. Application of such fluids makes it possible to easily control the viscosity coefficient through changes in the electric field in which the fluid is placed. It allows one

to easily adjust the damping coefficient in a dynamic system, for example in a power transmission system (Coulter *et al.*, 1993; Don and Coulter, 1995; Gamota and Filisco, 1991; Keşy *et al.*, 1997; Lee *et al.*, 1999; Li *et al.*, 1997; Ławniczak and Milecki, 1999; Weiss *et al.*, 1992). Therefore, such fluids have the potential to be widely used in different fields. Fundamental studies focus on power consumption (supply voltage 1-6 kV, current intensity 5-25 $\mu\text{A}/\text{cm}^2$, supply power 10 to 100 W), heat exchange, temperature rise and technical solutions. Problems that occur there are related to electric power supply (very high constant voltage, current breakdowns), temperature increments (double increase of voltage with every increase of temperature by 10-12°C), sensitivity to contamination of ER fluids. Current breakdowns cause disappearance of electric field at the electric field intensity $E > 5 \text{ kV}/\text{mm}$.

Electrorheological clutches with ER fluids have very low residual torque, unlike electromagnetic (EM) or magnetorheological (MR) clutches, which is important for many applications. A change of the torque transmitted by an ER clutch is made by a change of the supply voltage, which results in the change in the intensity of the electric field, and consequently, in the viscosity of the working fluid. ER fluids are incompressible, non-combustible, usually non-toxic or only slightly toxic, and they do not corrode. The effect of variable properties of ER fluids can be achieved for many mixtures of different oils and powders; however, the best properties are achieved for suspended polymers in silicon oil (Coulter *et al.*, 1993; Conrad, 1993; Gavin, 2001; Inoue *et al.*, 2002; Li *et al.*, 1997; Weiss *et al.*, 1994). An ER fluid of density of 1.06 g/cm^3 is a suspension of molecules of 1 to 100 μm in size. The molecules are graphitoidal, ceramic (silicone dioxide), and the polymers are in the form of a suspension in silicon or mineral oil. Technology of producing polymer-based fluids is very complicated. An ER fluid named the FL-Fluid, which is based on polymers, may be applied in a range of temperatures from -40 to 200°C . An ER fluid named the FL-Versa, which is mainly composed of linseed oil and limewater, has a smaller operating range from 10 to 90°C , but is considerably cheaper. FL fluids have the following properties: incompressible, non-toxic, they change from fluid to solid in around 0.001 s. An increase in temperature causes an increase in density of the current, but it also lowers the dynamic yield point. Depending on the shape of the working surface, there are two types of designs for clutches and brakes, i.e. disk-shaped and cylindrical.

The two types of ER fluids most frequently used in clutches and brakes (Don and Coulter, 1995; Gamota and Filisco, 1991; Keşy *et al.*, 1997; Li *et al.*, 1997; Weiss *et al.*, 1994) are diphasic and monophasic (homogenous) fluids. Diphasic fluids have the form of "suspensions" of dielectric molecules in

non-combustible fluids that exhibit reversible changes in rheological reaction when placed in an electric field (Don and Coulter, 1995; Gamota and Filisco, 1991; Weiss *et al.*, 1994). The fluid phase is often achieved with silicon oil (Conrad, 1993; Li *et al.*, 1997; Ławniczak and Milecki, 1999), which does not conduct electric current, and the solid phase is made by easily polarised mineral molecules, organic ones or polymers 2 to 10 μm wide, under the influence of an electric field. The presence of an electric field makes the polarised solid molecules join and form chains that inhibit movement of the fluid (Fig. 1).

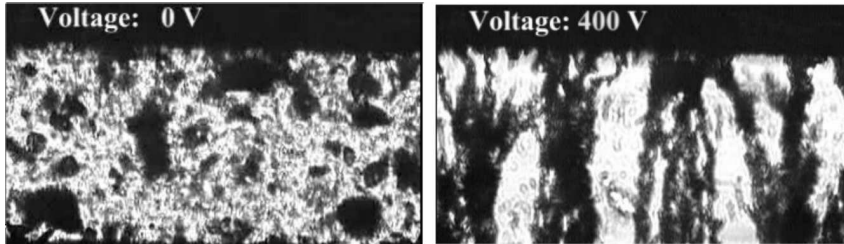


Fig. 1. Scheme of the ER fluid structure without (0 V) and with source of an electric field (400 V)

Monophase fluids are more rarely used than diphasé ones due to their very high cost. In ER fluids brought under the influence of an electric field of 1 kV up to 5 kV/mm, the shear stress τ ranges from 0.5 to 10 kPa. Diphasé fluids also contain stabilising substances that inhibit sedimentation of the solid phase due to the operation of centrifugal forces as well as inertia and gravitation. The percentage share of the solid phase is 60% to 85% in terms of weight and 20% to 40% in terms of volume.

Monophase fluids are "liquid crystals" for which the increase of shear stress (increase of the viscosity of the ER fluid) under the influence of an electric field is caused by a change in the orientation of the molecules in relation to the direction of the flow of the fluid. As a result of the electric field operation, an ER material transforms from the fluid to gel. In monophase fluids, adverse phenomena (coagulation, sedimentation, electrophoresis, mutual abrasion of the molecules) related to the presence of solid molecules do not occur.

2. Factors influencing rheological characteristics

Based on the results of the tests, characteristics will be determined in order to assess load transmissions on the output shaft of the tested clutch. The

experiments will differ depending on many factors and parameters that may be enumerated in two groups. The first group includes the following:

- type of the ER fluid used,
- geometrical parameters of the ER clutch, including above all the diameter and length of the rotor in the clutch,
- means of realisation of the flow of the ER fluid,
- type of the material used in the rotor electrode,
- size of the gap through which the ER fluid flows.

The second group includes the operating parameters, namely:

- voltage of the current flowing through the fluid in the gap,
- size of the anode surface,
- rotational speed of the rotor,
- working temperature of the fluid.

All of the above-mentioned factors essentially influence the rheological characteristics that illustrate the properties of the clutch.

Comprehensive and consistent solution to the two groups of problems can ensure proper operation of equipment with no breakdowns.

3. ER clutch structure for different rheological models

The fundamental issue in designing a power transmission system containing an ER clutch is the value of load transmitted in the form of torque depending on the shear stress τ . The value of τ depends on the type of ER fluid, power supply, conditions in which the clutch works as well as the design. In practice, the Bingham theoretical model (Kamath *et al.*, 1996) is most frequently assumed for analytical considerations (Fig. 2).

In considerations related to the flow of ER fluids, an assumption of laminar movement (flow) is made (Coulter *et al.*, 1993; Kamath *et al.*, 1996; Li *et al.*, 1997). The source of supply for the clutch is an external one, generated by a constant (DC) or changeable (AC) source of voltage U , as shown in Fig. 3. The ER fluid is treated as a Newtonian fluid. If the ER fluid is placed under the influence of an electric field, then the Bingham plastic model is assumed for the modelling. Interaction of the electric field makes the ER fluid in the preliminary phase – as linear strain increases – react as a solid. It starts to

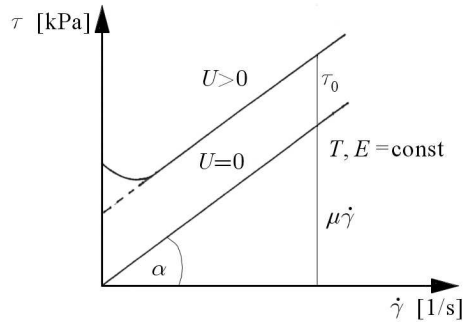


Fig. 2. Shear stress as a function of strain speed for the plastic Bingham model

”flow” when the shear stress τ between the layers of the fluid exceeds the threshold stress τ_0 . For a Newtonian fluid, τ is proportional to the speed of the linear strain (speed of shearing of the ER fluid layer) $\dot{\gamma} = d\gamma/dt$. The proportionality can be illustrated by the coefficient of dynamic viscosity μ , which has the form of the product of the coefficient of kinematic viscosity ν and density of the fluid ρ .

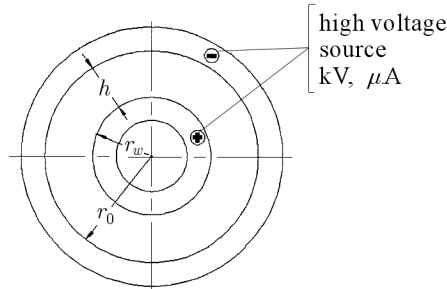


Fig. 3. Scheme of the power supply and geometric parameters of the ER clutch

Thus:

— for $\tau < \tau_0$ (Newton model)

$$\tau = \mu\dot{\gamma} = G\gamma \tag{3.1}$$

and (see Fig. 2)

$$\mu = \nu\rho = f(E) \quad \mu = \arctan \alpha \tag{3.2}$$

— for $E = \text{const}, T = \text{const}$ and $\tau > \tau_0$ (Bingham’s plastic model)

$$\tau = \mu\dot{\gamma} + \tau_0 \tag{3.3}$$

where: γ is the linear strain of the fluid, G – elasticity coefficient, τ_0 – threshold shear stress (yield point), T – working temperature of the ER fluid

$$E = \frac{V}{h} = \frac{RI}{h} = \frac{R\rho F}{r_0 - r_w} = \frac{2\pi r_{av} l R \rho}{r_0 - r_w} \quad r_{av} = \frac{r_0 + r_w}{2} \quad (3.4)$$

where: $h = r_0 - r_w$ denotes the thickness of the layer of the fluid (Fig. 3), l is the width of the gap between the rotor and clutch shell of the fluid, R – electric resistance, I – current intensity, F – shear surface of the ER fluid, r_0 – internal radius of the clutch shell, r_w – external radius of the rotor in the clutch (Fig. 3), r_{av} – average radius.

The dependence $\tau = f(\dot{\gamma})$ is called the rheological characteristic of an ER material. In the case of monophasic fluids, $\tau = 0$ (for $\dot{\gamma} = 0$ and $\tau_0 = 0$), while in diphasic fluids $\tau = \tau_0$ ($\dot{\gamma} = 0$).

3.1. Visco-plastic Bingham model

Identification of parameters of a clutch with an electrorheological fluid can be carried out based on different rheological models. Rheological models for electrorheological (ER) fluids are combinations of elements constituting perfect rheological bodies joined together in different ways. They represent perfect elastic bodies as in Hooke's law. Springs are characterised by elongation that is proportional to the applied force. They perfectly illustrate plastic properties of a St. Venant's body symbolically represented in the form of slip in dry friction conditions. They represent properties of a perfectly viscous Newtonian fluid (viscous damper). It is assumed in the literature on ER fluids that mechanical properties can be properly represented by a model constructed from two or three above-mentioned elements that are properly joined together. Visco-plastic rheological Bingham's models are discussed for example in papers Gamota and Filisco (1991), Kamath *et al.* (1996), Weis *et al.* (1994), and visco-elasto-plastic Bingham's models of bodies are presented in papers Gavin (2001), Kamath *et al.* (1996), Weis *et al.* (1994). The structure of both models is shown in Fig. 4.

In the model shown in Fig. 4a, the element representing moment of friction is joined parallelly with the linear viscous damper. The torque transmitted by the output shaft for a non-zero value of speed can be described with the following dependence

$$M = M_c \operatorname{sgn} \dot{\varphi} + c\dot{\varphi} \quad (3.5)$$

where: M_c is the moment of viscous friction of the perfectly viscous Newtonian fluid or moment of friction of the perfectly plastic St. Venant's body

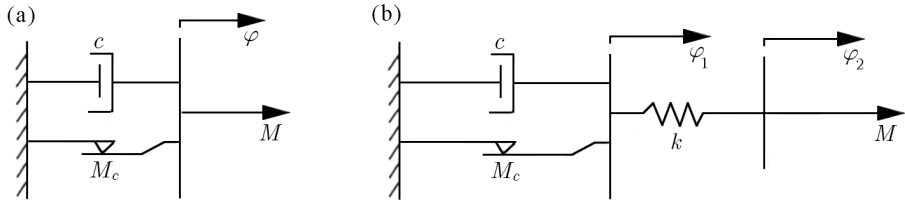


Fig. 4. Rheological structure of an ER clutch for Bingham's models: (a) visco-plastic model, (b) visco-elasto-plastic model

(Fig. 4b), φ – displacement in the form of an angle of torsion, $\dot{\varphi}$ – speed of the displacement, c – damping coefficient.

3.2. Visco-elasto-plastic Bingham's model of a body

Visco-elasto-plastic Bingham's model of a body illustrated in Fig. 4b can be described as follows

$$M = \begin{cases} M_c \operatorname{sgn} \dot{\varphi} + c\dot{\varphi}_1 + k(\varphi_1 - \varphi_2) & \text{for } |M| > M_c \\ k(\varphi_2 - \varphi_1) & \text{for } |M| \leq M_c \end{cases} \quad (3.6)$$

Bingham's visco-elasto-plastic model of a body differs from the visco-plastic model in the presence of an additional spring that represents spring properties of a Hooke's body. For big stresses, Bingham's model represents properties of an ER fluid, while for small stresses the model reacts like a solid. In the case of a torque not exceeding the value of the moment of static friction, the presented moment shows only a twist of the spring. Therefore, we have complete analogy to a solid. When the external moment exceeds the value of the St. Venant's moment of static friction, we observe simultaneous twisting of elements representing visco-plastic properties of the body, and the model will start to "flow". The "flow" phenomenon will take place when there exists a yield point and will occur in the moment when the shear stress τ reaches the threshold shear stress τ_0 . For stresses τ below the yield point, the fluid maintains properties of a viscous-elastic body. Therefore, in the case when the shear stress τ in the Bingham model is smaller than the threshold stress τ_0 , the equation of state takes a form analogous to equation (3.1) describing the properties of an elastic body. When the stresses τ in the Bingham model exceed stresses τ_0 , then the state of stresses can be described with equation (3.3).

3.3. Visco-elasto-plastic Gamota-Filisco model

The rheological model proposed by Gamota and Filisco (1991) (Fig. 5) is an enhancement of the visco-plastic Bingham model (Fig. 1a). The design of this model is based on the basic Bingham model of a body as a visco-plastic model that is enriched with elements in series representing visco-elastic properties of a Newtonian fluid. These properties appear in the form of a Kelvin-Voigt's body with additional elastic properties in the form of a Hooke's body.

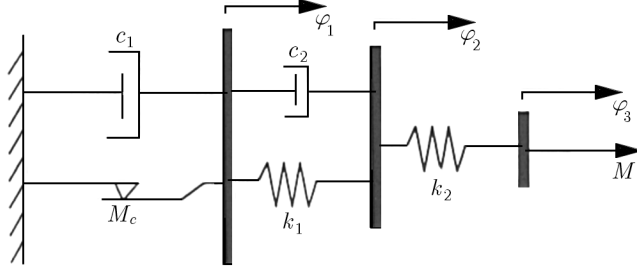


Fig. 5. Rheological structure of an ER clutch for visco-elasto-plastic Gamota-Filisco's model

In this model, the torque transmitted by the output shaft of the clutch can be described as follows:

— for $|M| > M_c$

$$M = c_1 \dot{\varphi}_1 + M_c \operatorname{sgn} \dot{\varphi}_1 + c_2(\dot{\varphi}_2 - \dot{\varphi}_1) + k_1(\varphi_2 - \varphi_1) + k_2(\varphi_2 - \varphi_3) \quad (3.7)$$

or

$$M = c_1 \dot{\varphi}_1 + M_c \operatorname{sgn} \dot{\varphi}_1 = c_2(\dot{\varphi}_1 - \dot{\varphi}_2) + k_1(\varphi_1 - \varphi_2) = k_2(\varphi_3 - \varphi_2) \quad (3.8)$$

— for $|M| \leq M_c$, $\varphi_1 = 0$

$$M = c_2 \dot{\varphi}_2 + k_1 \varphi_2 + k_2(\varphi_2 - \varphi_3) \quad (3.9)$$

or

$$M = c_2 \dot{\varphi}_2 + k_1 \varphi_2 = k_2(\varphi_3 - \varphi_2) \quad (3.10)$$

where: c_1 , M_c are parameters representing damping and moment of friction in Bingham's model, c_2 , k_1 – parameters describing damping and stiffness of Kelvin-Voigt's model (of the body), k_2 – stiffness of the spring in Hooke's model (of the body).

When $|M| \leq M_c$, then $\varphi_1 = 0$, and then the value of the moment of friction M_c related with stress in the ER fluid is bigger than the moment M on the output shaft, which means that the shaft remains still.

3.4. Visco-elasto-plastic Li's model

Visco-elasto-plastic properties of an ER fluid are suitably represented by a more sophisticated model proposed by Li *et al.* (1997), as shown in Fig. 6.

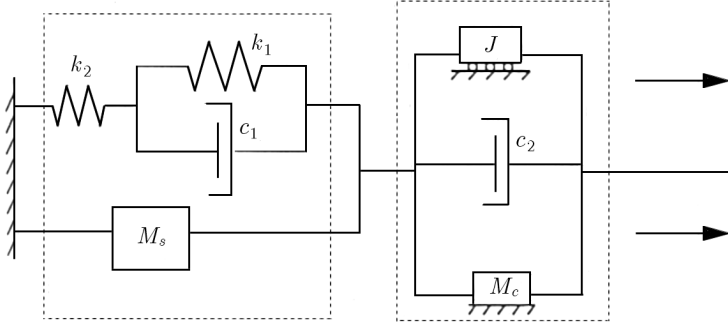


Fig. 6. Rheological structure of an ER clutch for visco-elasto-plastic Li's model

The model is composed of two basic parts characterising the hysteresis loop in the form of a preliminary and final course. In the first part of the model, the course of the function is represented by a combination of Kelvin-Voigt's model composed of the damper c_1 and spring k_1 with a perfect elastic Hooke's body (spring k_2) and an element that is represented by the static moment M_s . The total moment M consists of M_s and a moment M_ν resulting from the cooperation of visco-elastic properties of the structure of elements of the first part of the model (Fig. 6).

The total moment generated by the structure can be described as follows

$$M = M_s + M_\nu \quad (3.11)$$

where

$$M_\nu = \frac{k_1 k_2}{k_1 + k_2} \varphi + c_1 \dot{\varphi} \quad (3.12)$$

Thus

$$\dot{M}_\nu + \frac{k_1 + k_2}{c_1} M_\nu = \frac{k_1 k_2}{c_1} \varphi + k_2 \dot{\varphi} \quad \dot{M}_\nu = k_1 \dot{\varphi} \quad (3.13)$$

The second part of the Li model is represented by a viscous damper c_2 , a body with the moment of inertia J and the moment of friction M_c . Therefore

$$J\ddot{\varphi} + c_2\dot{\varphi} + M_c \operatorname{sgn} \dot{\varphi} = M \quad (3.14)$$

4. Calculation of torque transmitted by the tested ER clutch

In order to calculate the torque transmitted by an ER clutch, its rheological characteristic is necessary. Such a characteristic can be determined by means of appropriate laboratory tests. The means for determination of rheological characteristics have not been normalised so far. Experimental testing is on way to find the dependence between the results of measured parameters (width of gap, size of electrodes, work conditions, power supply) determined in different ways. The findings are still ambiguous, see e.g. Coulter *et al.* (1993), Gavin (2001), Li *et al.* (1997), Weiss *et al.* (1994). In an ER clutch, there are several elements joining the drive and driving part through the ER fluid, bearings, seals, additional frictional elements.

The total torque M transmitted by the ER clutch can be determined from the sum of partial torques, i.e.

$$M = M_{ER} + M_{tl} + M_{tu} + M_k \quad (4.1)$$

thus

$$M_{ER} = M - (M_{tl} + M_{tu} + M_k) \quad (4.2)$$

where: M_{ER} is the torque transmitted by the ER fluid, M_{tl} – friction torque transmitted by bearings, M_{tu} – friction torque transmitted by seals, M_k – friction torque transmitted by the brush and commutator.

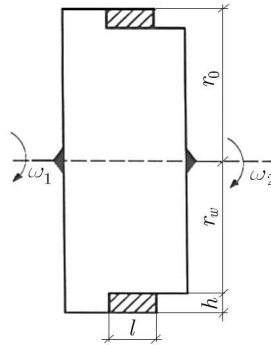


Fig. 7. Main parameters for ER clutch calculations

The torque M_{ER} transmitted by the ER clutch (Fig. 7) can be determined from the following relationship

$$M_{ER} = Fr_{av}\tau \quad (4.3)$$

where: ω_1 denotes the angular velocity of the driving part of the clutch, ω_2 – angular velocity of the driven part of the clutch.

Having taken into account the following

$$F = 2\pi r_{av} l \quad r_{av} = \frac{r_0 + r_w}{2} \quad (4.4)$$

the below-specified dependence can be derived from formulas (4.3) and (4.4)

$$\tau = \frac{2M_{ER}}{\pi l (r_w + r_0)^2} \quad (4.5)$$

For $\omega_1 = \omega_2 = \omega$, in accordance with papers by Coulter *et al.* (1993), Kamath *et al.* (1996), Ławniczak and Milecki (1999)

$$\dot{\gamma} = \frac{\omega r_{av}}{h} = \frac{\pi n r_{av}}{30h} = \frac{\pi n (r_w + r_0)}{60(r_0 - r_w)} \quad h = r_0 - r_w \quad (4.6)$$

Finally, the following can be derived from formula (4.3) with the use of formulas (4.4) and (4.6)₁

$$M_{ER} = \frac{\pi^2 r_{av}^3 l \mu n}{15h} + 2\pi r_{av}^2 l \tau_0 \quad (4.7)$$

where: n is the rotational speed of the rotor [rpm], ω – angular velocity of the rotor [rad/s].

The shear stress τ_0 occurring in formula (4.7) can be experimentally determined from a graph showing the torque as a function of the rotational speed.

In the case of modelling rheological properties of the ER fluid with formula (3.1), the following parameters have to be assumed in equation (3.3): $\tau_0 = 0$, $\mu = \mu_p$ (μ_p – apparent viscosity coefficient, plastic viscosity), then equation (4.7) assumes the following form

$$M_{ER} = \frac{\pi^2 n \mu_p r_{av}^3 l}{15h} \quad (4.8)$$

For $\omega_1 > \omega_2$ in accordance with (Coulter *et al.*, 1993; Kamath *et al.*, 1996; Ławniczak and Milecki, 1999)

$$\dot{\gamma} = \frac{\omega_1 r_0 - \omega_2 r_w}{h} \quad (4.9)$$

The ER fluid, which is under the influence of the electric field, is a Bingham's fluid. It makes it possible to use dependence (3.3) for calculations of τ . If we substitute formulas (3.3), (4.4)₁ and (4.9) to equation (4.3), we obtain

$$M_{ER} = \frac{2\pi r_{av}^2 l \mu \omega_1 (r_0 - i_k r_w)}{h} + 2\pi r_{av}^2 l \tau_0 \quad i_k = \frac{\omega_2}{\omega_1} \quad (4.10)$$

where i_k is the kinematic ratio.

When no electric field is applied to the ER fluid ($\tau_0 = 0$) (Newton's model), then the first components appear in formulas (4.7) and (4.10)₁. When the electric field does operate (Bingham's model), then the sum of components appears in these formulas.

5. Measurement system in the ER clutch test stand

A scheme of the mechanical structure and measurement system of the prototype test stand for an electrorheological clutch filled with an ER fluid is shown in Fig. 8.

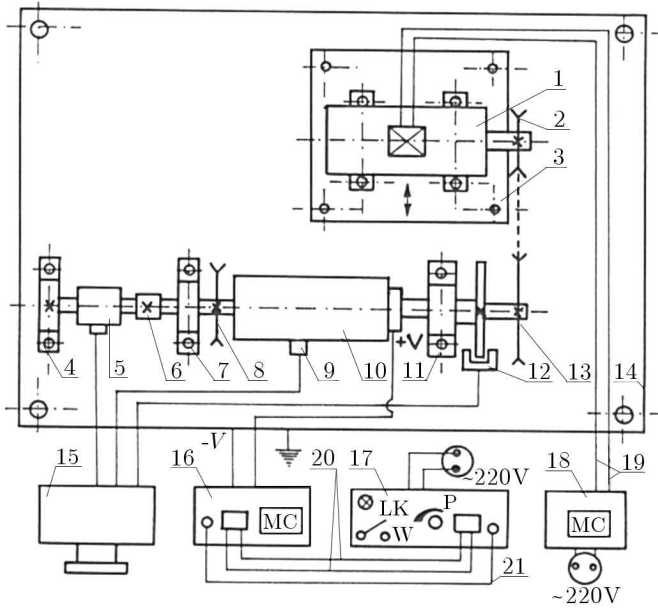


Fig. 8. Scheme of mechanical structure and measurement system of the test stand for an ER clutch: 1 – asynchronous motor, 2 – driving wheel, 3 – motor skid plate, 4 – torque meter contact clip, 5 – torque meter, 6 – spring collet, 7, 11 – bearing' shells, 8 – belt pulley, 9 – temperature sensor, 10 – tested ER clutch, 12 – rotational speed sensor, 13 – driven wheel, 14 – test stand base, 15 – PC computer with AC/CA measurement card, 16 – high voltage module, 17 – high power generator, 18 – frequency converter, 19 – electric wiring for asynchronous motor supply, 20 – electric wiring for MC digital meter, 21 – electric wiring for high voltage module (16) from high power generator (17), $-V$, $+V$ – special high voltage electric wiring for ER clutch supply ($-$ mass wire, $+$ supply wire), LK – control lamp, W – switch

The ER clutch is composed of two basic elements in the form of loosely joined cylinders of different diameters. The main elements are: the rotor constituting the anode and the shell constituting the cathode (Fig. 3). These parts are electrically isolated one from the other and joined with poles of continuously regulated high voltage with the maximum power of 38 W. The source of high voltage is composed of high power generator (17) and high voltage module (16) with digital voltage meter (MC). Double conductor (20) feeds the digital voltage meter (MC) built into (16). The source of supply for (MC) is in (17). The alternating voltage signal from (17) is transmitted to (16) by conductor (21). The ER fluid is placed in the gap of width h between cylinders (Fig. 3). The diameter of the internal part of the shell (cathode) is 104 mm; and the cathode is 150 mm long. The external diameter of the isolated collet of the rotor (anode) has 100 mm, and its width (thickness of the ER fluid) between the cylinders is $h = 2$ mm.

The tested ER clutch is driven by an asynchronous motor (1) with power of 1.5 kW, fed from frequency converter (18). The frequency converter (controller) with a built-in PID regulator makes it possible to change rotational speed of the motor shaft or to maintain it within a precisely specified range. Rotational speed is regulated by a potentiometer built into the system – it allows for continuous regulation of the rotational speed. The rotor of tested ER clutch (10) is joined with torque meter (5) with spring collet (6), while the output shaft of the torque meter is permanently fixed to the test stand base (14) with contact clip (4) of torque meter (5).

Based on the preliminary results of tests, the following range of parameters was assumed for further testing: rotational speed up to 1200 rotations per minute ($\omega \cong 120$ 1/s) due to working temperature of the clutch, supply voltage up to 3 kV due to potential breakdowns, volume of the fluid – 102 μ l in order not to exceed the maximum power of the high voltage feeder.

In the course of experimental tests carried out on the laboratory stand, the following is measured: braking torque M of rotor (5), supply voltage U of clutch (10), rotational speed n (12) of the drive part (ER clutch shell) as well as temperature of the ER fluid, clutch shell (10) and bearings (7,11). Temperature of the shell is measured with a thermo-vision camera. Temperature measurements for the shells of the rotor bearings are realised with built-in thermocouples. After one hour and a half of the test stand operation, a steady state occurs for temperatures in the whole kinematic chain of the cooperating elements. Measurements are taken for the specific temperature of the fluid, constant supply voltage of different values for different values of angular velocity. The results of the measurements are registered on the PC computer

equipped with an AC/CA measuring card. Different ER fluids with basic properties specified by a manufacturer can be used in the tests. The shear stress τ , shear speed $\dot{\gamma}$ and current intensity per millimeter-thick layer of the fluid at an appropriate voltage E can be assumed based e.g. on papers Coulter *et al.* (1993), Don and Coulter (1995), Lee *et al.* (1999), Li *et al.* (1997). The tested ER clutch is shown in Fig. 9.

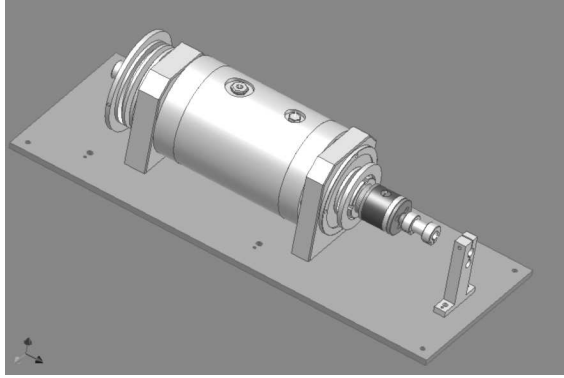


Fig. 9. Tested electrorheological clutch

The test stand is shown in Fig. 10.

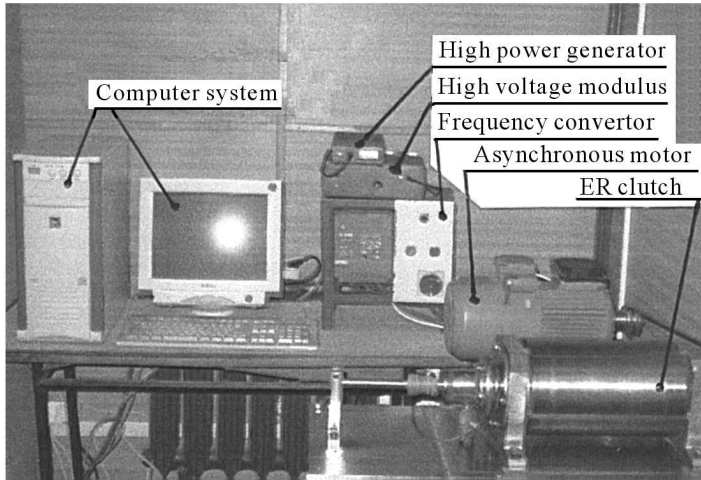


Fig. 10. Test stand

While selecting an ER material, we assume such a value of the shear stress τ_0 or apparent viscosity μ_p so that to avoid electric breakdown and not to exceed acceptable power of high voltage feeder P_{max} . In order to avoid

breakdowns, the type of ER fluid and the value of supply voltage must be matched with the width of the gap and the surface of the electrodes. In this case, the surface of the electrodes is equal to the external surface of the cylinder of the rotor (shear surface of the ER fluid). The average density of current $\rho = 15 \mu\text{A}/\text{cm}^2$, supply voltage $U = 2.8 \text{ kV}$, length of the rotor $l = 150 \text{ mm}$, external radius of the rotor $r_w = 50 \text{ mm}$.

Maximum power provided can be determined from the following formula

$$P_{max} = UI = U\rho F = 2\pi r_w l \rho U \cong 20 \text{ W} \quad (5.1)$$

The current density decreases as the shear speed increases. It increases as a result of rising temperature of the ER fluid. A chemical product – electrorheological (ER) fluid LID 3354 S made by Smart Technology LTD, England, Birmingham – was applied for mechanical testing. This ER fluid is made up of 23% silicone oil, 37.5% lithium salt of resorcinol/formaldehyde polymer, 39.5% chloro-fluoro-polymer. The characteristics of this fluid are shown in Fig. 11.

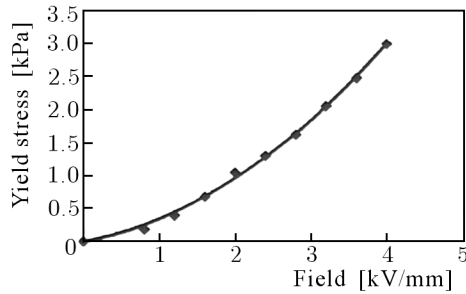


Fig. 11. Shear stress versus electric field

Its physical properties are as follows: density $1.46 \cdot 10^3 \text{ kg}/\text{m}^3$, viscosity $110 \text{ mP}\cdot\text{sec}$ at 30°C , current density $5 \mu\text{A}/\text{cm}^2$, boiling point $> 200^\circ\text{C}$, flash point $> 150^\circ\text{C}$, freezing point -20°C . It is insoluble in water, and it does not attack elastomers.

6. Conclusions

The results of experimental tests make it possible to:

- assess the applicability of "intelligent" ER fluids in view of requirements that such fluids need to meet

- estimate capability of external load transmission and determine the influence of temperature on that transmissibility
- evaluate accuracy of the technical solution, especially leak tightness, and resistance to breakdowns related to ER fluids as well as isolation elements in the test stand, plus limitations on resistance to motion and durability.

The obtained results will constitute the basis for introducing modifications to the existing solutions and applying them in practice to different mechanical systems. Based on analytical considerations and experimental tests on the prototype ER clutch, appropriate conclusions will be formulated.

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Czynniki wpływające na przenoszenie obciążenia przez elektoreologiczne sprzęgło cylindryczne

Streszczenie

W artykule omówiony jest wpływ czynników na charakterystyki reologiczne sprzęgła. Dla różnych modeli reologicznych określono zależności na moment przenoszony przez wał wyjściowy sprzęgła. Główna część pracy poświęcona jest reologicznemu modelowaniu elektoreologicznego sprzęgła cylindrycznego. Do omawianych modeli reologicznych włączono: lepko-plastyczny i lepko-sprężysto-plastyczny model Binghama, lepko-sprężysto-plastyczny model Gamota-Filisko i Li. Opisano układ pomiarowy stanowiska badawczego i jego możliwości badawcze. W pozostałej części pracy omówiono charakterystyki płynów elektoreologicznych ER. Wyznaczono także kierunki przyszłych badań na stanowisku laboratoryjnym zaprojektowanym i wykonanym przez autora .

Manuscript received June 26, 2008; accepted for print October 2, 2008