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# DURABILITY OF HYDRAULIC CLUTCHES FILLED WITH ELECTRORHEOLOGICAL FLUIDS

# TRWAŁOŚĆ SPRZĘGIEŁ HYDRAULICZNYCH Z CIECZAMI ELEKTROREOLOGICZNYMI

Abstract

The paper presents the results of experimental tests concerning the durability of two devices, using three different electrorheological fluids as working fluids. They were: a cylinder viscous brake and a dual clutch, consisting of a cylinder viscous clutch and a hydrokinetic clutch. The concept of the control of devices filled with electrorheological working fluids involves the impact of the electric field of variable intensity on the working fluid and thus causes changes of sheer stress in it. It also changes the transmitted torque. The studies show that the most important factors affecting the durability of a viscous brake and a dual clutch are: sealing of the workspace, including the electrorheological fluid, electrorheological fluid type, electrodes and electrical wire insulation, supplying high voltage from the power supply. Another essential factor is that the durability of the electrorheological fluid, defined by the rate of wear, is found within the ranges reported in the literature and does not differ significantly from the magnetorheological fluid durability.

*Keywords: Durability, viscous clutches and brakes, hydrokinetic clutches, adaptive fluids*

Streszczenie

W artykule przedstawiono wyniki badań eksperymentalnych trwałości dwóch urządzeń, w których zastosowano trzy różne ciecze elektroreologiczne jako ciecze robocze. Były to: wiskotyczny hamulec cylindryczny oraz sprzęgło zespolone, składające się z wiskotycznego sprzęgła cylindrycznego i sprzęgła hydrokinetycznego. Koncepcja sterowania urządzeń z elektroreologicznymi cieczami roboczymi polega na oddziaływaniu polem elektrycznym o zmiennym natężeniu na ciecz roboczą i wywoływaniu w ten sposób zmian naprężeń stycznych w cieczy roboczej, a tym samym zmian przenoszonego momentu obrotowego.Z przeprowadzonych badań wynika, że najistotniejszymi czynnikami wpływającymi na trwałość hamulca wiskotycznego i sprzęgła zespolonego są: uszczelnienie przestrzeni roboczej, w której znajduje się ciecz elektroreologiczna, rodzaj cieczy elektroreologicznej, izolacja elektrod i przewodów elektrycznych, doprowadzających wysokie napięcie z zasilacza oraz że trwałość cieczy elektroreologicznych, zdefiniowana za pomocą stopnia zużycia, mieści się w zakresach podawanych w literaturze. Ponadto nie odbiega znacznie od trwałości cieczy magnetoreologicznych.

*Słowa kluczowe: trwałość, sprzęgła i hamulce wiskotyczne, sprzęgła hydrokinetyczne, ciecze adaptacyjne*

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## 1. Introduction

Currently, the main direction of research and development concerning machine drive systems is to improve the design of their components, such as clutches, brakes or gears. The application of new hydraulic fluids causes the progress of clutches and brakes. Due to the issue of increasing demands concerning drive units, which is connected with the increase of machine efficiency, new components must be very durable. The durability is defined as the machine's ability to preserve the functionality in the required conditions of its use. The device durability has an essential impact on its reliability.

Hydraulic clutches consist of a driving part, combined with an input shaft, a driven part, connected to the output shaft, and a working fluid. There are two basic types of clutches: viscous and hydrodynamic ones. In viscous clutches, driving and driven parts are connected together due to the friction caused by shear stresses $\tau$ in the working fluid, while in the hydrokinetic clutches, the torque is transmitted from the pump impeller to the turbine impeller, using the kinetic energy of the working fluid.

Due to the workspace shape, the following can be distinguished: viscous couplings – cylindrical and disc clutches and hydrodynamic ones, including or not including the inner ring. By immobilizing the driven part of the hydraulic clutch, it can be converted into a hydraulic brake.

Working fluids called adaptive fluids or smart fluids, in which the shear stress can be changed by means of an electric current [1, 2], are used in hydraulic clutches and brakes. They are: electrorheological fluids that are activated with the electric field and magnetorheological fluids activated with the magnetic field. The concept of hydraulic clutch control filled with these fluids is based on the interaction of the electric or magnetic field of variable intensity on the working fluid and thus inducing shear stress changes in the working fluid and consequently changes of the transmitted torque [3, 4].

Considering the composition, both electrorheological and magnetorheological fluids are divided into heterogeneous fluids, consisting of a solid phase and a liquid phase and a homogeneous fluids. Heterogeneous fluids are mostly used in hydraulic clutches. The solid phase in this type of fluid is present from 20% to 80%, and from 5% to 50% as far as volume is concerned. The increase in shear stress in heterogeneous fluids, when being influenced by electric or magnetic fields, is caused by the creation of spatial structures hindering the flow of the mixture.

Solid particles of heterogeneous adaptive fluids are about a few micrometers in diameter and are made (in case of electrorheological fluids) of materials that are polarized when influenced by an electric field. They can also be made of inorganic materials (metal oxides, zeolites, glass) or organic ones (starch, resins, rubber, polyaniline, polyphenylene). In the case of magnetorheological fluids, they are made of materials with ferromagnetic properties [5–8]. A non-conductive liquid, typically oil or silicone oil, is used as a liquid phase. These fluids also contain various types of additives modifying their properties (water, inorganic salts, acids, alcohols, esters). These additives prevent particle sedimentation and combination so that they can be used in a wide range of temperatures and with considerable accelerations.

In viscous clutches and brakes including electrorheological fluids, in order to generate an electric field, electrodes, which are also elements of driving and driven parts of the clutch, are used. On the contrary, to induce a magnetic field in the clutches and brakes of magnetorheological fluids, it is necessary to use additional electromagnets. For these reasons, clutches and brakes including electrorheological fluids have a much simpler construction. The disadvantage of these clutches and brakes are their bigger dimensions in comparison with clutches and brakes including magnetorheological fluids, resulting from the fact that the maximum shear stress, possible to obtain during the activation, is several times greater in magnetorheological fluids than in electrorheological fluids. It is possible to obtain the range of shear stress changes, which can be influenced by means of an electric current through the formation of one of the physical fields. It allows for over one hundred times more precise and continuous variation of the torque transmitted by viscous clutches or brakes.

Up till now, a number of clutches and brakes using electrorheological or magnetorheological fluids as working fluids [9–13] have been developed and tested. However, in mass-produced machines, these clutches are rarely used [14]. For this reason, there are no experiments connected with the durability of such clutches and brakes.

## 2. Review of literature concerning the durability of equipment including adaptive fluids

Previous studies concerning the durability of devices filled with adaptive fluids have concentrated mainly on studying clutches and dampers, referring to the fluid durability, whole devices or their components.

The authors of the publication [15] suggest two reasons for the electrorheological fluid degradation: high operating temperature and the phenomenon of electrolysis, caused by the flow of the electric current through the liquid. During the process of electrolysis, chemical reactions may occur, resulting in the decomposition of water, and oxidation or reduction of the material, of which adaptive fluid particles are made. The corrosion of the electrode material might also occur. As it is seen from the example given in the publication, the water content of the electrorheological fluid sample may be reduced up to 1% when the current flow is 10 mA for 600 hours. The change of the electrorheological fluid property can also be caused by the degradation of inorganic salt particles added to electrorheological fluids in order to improve their electrical conductivity. In this case, a decrease of shear stress $\tau$ in the electrorheological fluid can be noticed. For the fluid consisting of polymer particles and silicone oil, the shear stress decrease may be $\tau$ approx. 40% when the current flow is 50 μA for 3 hours.

In the paper [16], the impact of the temperature on the shear stress $\tau$ in the newly developed electrorheological fluid, consisting of polyurethane particles and silicone oil, has been studied by means of reometer, which has a special construction. It was found that the detention of the liquid for 1000 hours at a temperature below 60°C does not change the shear stress value, but instead raises the temperature to:

– 100°C decreased the value of shear stress by 50% after 100 hours,
– 120°C decreased the value of shear stress by 40% after 4 hours.

On the basis of the durability of the linear damper including the magnetorheological fluid, it has been found that the first sign of the magnetorheological fluid wear is the value increase of the coefficient of dynamic viscosity in time, due to the particle disintegration [17]. Moreover, it has been established that the destruction of even a small number of solid particles causes a significant increase in the coefficient of dynamic viscosity. The problem of the low durability of particles has been solved by changing the way they are received.

In the paper [18], a pin-on-disc wear apparatus has been used to carry out the tribological experiment for the magnetorheological liquid. It has been found that the sample wear rate with the magnetic field is higher than without it. The wear rate is in proportion to the rotating speed and rotating load.

In a similar manner, the magnetorheological fluid, intended for the use in a damper, has been tested [19]. Experimental studies consisted of the oscillating motion of the piston rod in a groove cut in a cube made of sealing material filled with magnetorheological fluid or a typical hydraulic oil. The load was 80 N, the amplitude was 7 mm, and the oscillation frequency was equal to 10 Hz. The test duration varied and ranged up to 48 hours. The piston rod wear was evaluated on the basis of measuring its surface roughness. After conducting the experiments, it was found that the measured wear of the piston rod is much greater when the magnetic fluid is used.

In [17, 20] papers, a method has been suggested for determining the durability of the magnetic fluid by means of $S$ wear degree on the basis of the energy (converted into heat during the device operation) ratio, to the fluid volume, defined as:

$$S = \frac{1}{V}\int_0^t P dt \qquad (1)$$

where:

- $P$ – the power converted to heat,
- $V$ – liquid volume,
- $t$ – time.

It has been assumed that the device works properly when the condition is fulfilled:

$$S > S_b \qquad (2)$$

where:

- $S_b$ – limit value of the wear degree for the magnetic liquid from $10^5$ J/cm$^3$ to $10^7$ J/m$^3$.

A new electrorheological fluid studied in the paper [16] has been investigated in a damper. During the tests, the damper piston travelled 40 km, and the damper filled with 200 ml of liquid $1.7 \times 10^7$ J scattered the energy, which means that the wear degree $S$ defined in the papers [17, 20] was equal $0.85 \times 10^5$ J/cm$^3$. After the tests have been completed, no degradation of the electrorheological fluid, seal damage, or other elements of the damper have been found.

The publication [14] presents the results concerning the research on the durability of the clutch filled with magnetorheological fluid, destined for the drive of the cooling system fan used in a vehicle. The durability test has been based on the clutch work, operating on the test rig for 500 hours at various speeds of the input shaft (600, 1600, 2000, 2700 rev/min). The torque transmitted by the clutch is proportional to the square of the angular velocity of its input shaft. After the completion of the test, no changes in the clutch performance were noticed. The degree of the adaptive liquid $S$ wear, defined in papers [17, 20], was equal to $7.3 \times 10^7$ J/cm$^3$.

According to the results of the studies, the most important factors affecting the durability devices filled with adaptive fluids are:

- electrorheological fluid (quantity, composition, particle construction),
- fluid working conditions (temperature, the amount of dissipated energy, ambient humidity),
- construction of the device (sealing, materials).

It should also be pointed that, currently, there is no uniform method for testing the durability of devices filled with adaptive fluids. The values of wear degree *S* calculated for the tested clutches and dampers exceed the value range of values from $10^5$ J/cm$^3$ to cm$^3$ to $10^7$ J/cm$^3$ suggested in the publication [17, 20]. It indicates the need for further research concerning ways of evaluation of durability of devices filled with adaptive fluids. Therefore, when implementing devices filled with new adaptive fluids, it is necessary to develop tailor-made durability tests.

## 3. Mathematical relationships used to assess the durability of clutches and brakes filled with adaptive fluids

In hydraulic clutches and brakes, both cylindrical and disc, the value of the transmitted torque $M$ is proportional to the shear stress $\tau$ in the liquid and the value of angular velocity to sheer rate $\dot{\gamma}$. The following dependencies are practically used for clutches and cylindrical brakes [21]:

$$\tau = \frac{M}{2\pi r_1^2 b} \quad \dot{\gamma} = \frac{r_1 \omega}{r_2 - r_1} \tag{3}$$

or

$$\tau = \frac{M}{2\pi r_2^2 b} \quad \dot{\gamma} = \frac{r_2 \omega}{r_2 - r_1} \tag{4}$$

where:

$r_1$ – the radius of the inner cylinder,
$r_2$ – the radius of the outer cylinder,
$b$ – width of the cylinders,
$\omega$ – relative velocity of cylinders, Fig. 1.

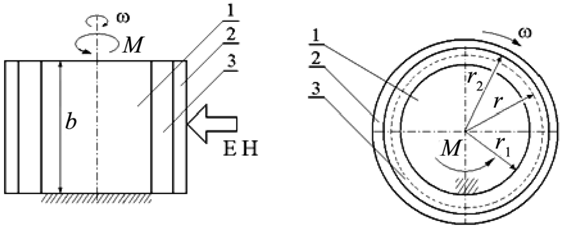



Fig. 1. Scheme diagram of the viscous clutch or brake: 1 – stationary cylinder, 2 – driven cylinder, 3 – gape filled with electrorheological fluid

Rheological properties of adaptive fluids are usually presented by means of dependencies of shear stress $\tau$, occurring in the fluid, to shear rate $\dot{\gamma}$. The product of these two quantities determines the power $P$ of the clutch or brake assuming constant working conditions, related to the volume $V$ of the used fluid:

$$\tau\dot{\gamma} = \frac{P}{V} \tag{5}$$

During design calculations of hydraulic clutches and brakes filled with adaptive fluids, Bingham model is often used. There, the shear stress $\tau$ in the fluid, for the constant value of the electric or magnetic field strength, is defined as:

$$\tau = \mu_p \dot{\gamma} + \tau_0 \tag{6}$$

where:

$\mu_p$ – plastic viscosity,

$\dot{\gamma}$ – shear rate $\tau_0$ – limit strength dependent respectively on electric $E$ or magnetic $B$ field strength, Fig. 2.

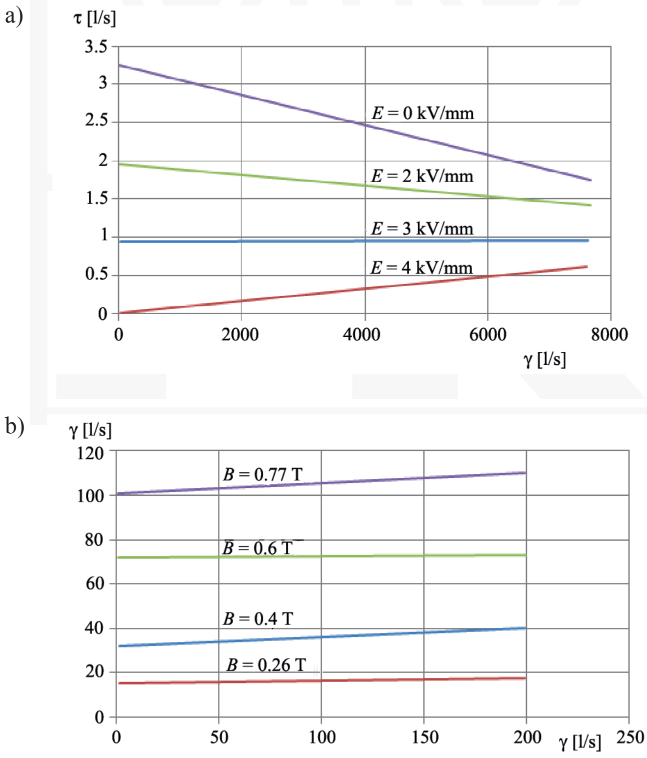



Fig. 2. Fluid rheological characteristics described by means of Bingham model: a) electrorheological fluid [22], b) magnetorheological fluid [23]

The formula (1), defining the wear degree $S$, in the case of hydraulic clutches and brakes filled with adaptive fluids and described with Bingham model, can be written in the following way:

$$S = \frac{P}{V} t = \tau \dot{\gamma} t = (\mu_p \dot{\gamma} + \tau_0) \dot{\gamma} t \tag{7}$$

As it is seen from Fig. 1, parameter value: $\mu_p$ and $\tau_0$ in Bingham model, as well as the wear degree $S$, are significantly changed due to the electric field value. This change refers particularly to electrorheological fluids. The impact of the shear rate on the fuel wear degree is parabolic, and the impact of a device working time – linear. It should be noted that the plastic viscosity $\mu_p$ which is equal to the arc tangent of the angle of the straight varies due to the increase of the electric $E$ and magnetic $B$ field strength. Values differ from positive to negative ones. On the contrary, yield strength $\tau_0$, determined for $\dot{\gamma} = 0$ always increases due to electric or magnetic field strength. Thus, it is possible that, depending on the parameter values $\mu_p$ and $\tau_0$, the degree of the device wear will diminish together with the increase of angular velocity, which is not possible for typical hydraulic clutches.

For hydraulic clutches and brakes filled with adaptive fluids, in constant conditions, the wear degree $S$ can be calculated on the basis of the formula (1) converted as follows:

$$S = \frac{P}{V} t = \frac{t}{V} \omega M \tag{8}$$

where:

- $P$ – power delivered to the clutch,
- $V$ – working fluid volume,
- $t$ – time job working fluid in the clutch,
- $\omega$ – the relative angular velocity,
- $M$ – torque transmitted by the clutch.

The minimum volume $V$ of the fluid ensuring the proper operation of viscous brake can be calculated from the dependence [24]:

$$V = \left( \frac{\mu_p}{\tau_0^{\,2}} \right) \left( \frac{M_\tau}{M_\mu} \right) \left( M_\tau \, \omega \right) \tag{9}$$

where:

- $M_\mu$ – torque in case of adaptive fluid activation absence,
- $M_\tau$ – torque in case of adaptive fuel activation,
- $\omega$ – relative angular velocity.

In practice, the liquid volume used in prototype valves, linear dampers as well as clutches filled with the magnetorheological fluid, is much greater than the one calculated according to formula (9) and takes values from 25 V to 50 V [20].

## 4. Hydraulic clutches and brakes filled with adaptive fuels durability tests

The durability test was performed for a cylindrical viscous brake and a dual clutch, which consisted of a cylinder viscous clutch and a hydrodynamic clutch, filled with various electrorheological fluids. A cylindrical viscous brake was mounted directly on the axis of the electric motor engine. The bearings of the driving brake part were inside the brake, whereas driving and driven parts of the dual clutch were mounted outside the clutch.

### A. Cylindrical viscous brake durability testing

A cylindrical viscous brake, as shown in Fig. 3, consists of two cylindrical parts with different diameters, forming electrodes, electrically isolated from each other, which are connected to the high voltage power supply through the commutator and electric wires [25, 26]. The cylinders are made of aluminum. The external diameter of the brake is 160 mm and its width 90 mm. The size of all construction joints, filled with the working fluid, is 1 mm.

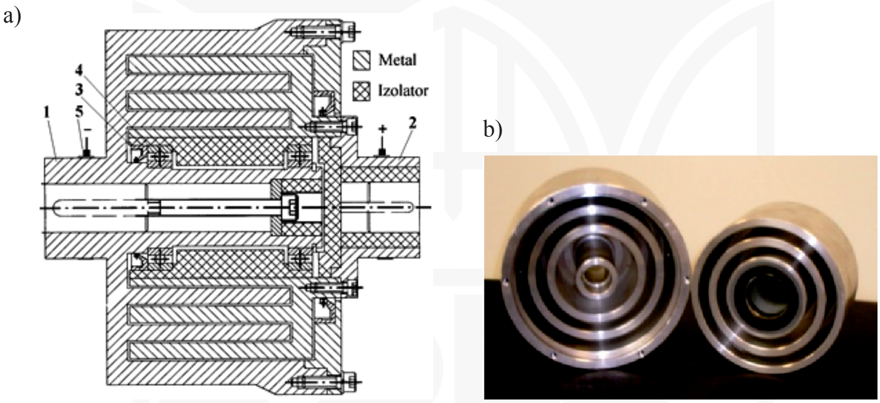



Fig. 3. Scheme of the cylinder viscous brake design; a) cross-section: 1 – driven element of the brake, 2 – a stationary brake part 3 – sealing ring 4 – ball bearing 5 – commutator rings; b) general view

The driven part of the brake is located on ball bearings installed on a sleeve connected to an external part of the brake, sealed with a typical sealing ring.

The brake was filled with two different electrorheological fluids. The data is presented in Table 1.

Table 1

**The basic data of the tested ER [4]**

| Fluid symbol | Manufacturer | Density [kg/m$^3$] | Fluid volumetric composition | Volume [cm$^3$] |
|---|---|---|---|---|
| LID 3354S | Smart Technology Ltd, UK [ 22] | 1460 | 37% polymer, silicone oil | 140 |
| CES35 | Technical University in Radom, PL | 95 | 35% soluble starch, transformer oil | 140 |

A dual clutch mounted on the test rig, as shown in Fig. 4, enables the measurement of the angular velocity ω and the transmitted torque *M*. During the test, the voltage 1 kV was adjusted to the brake cylinders.

a) b)

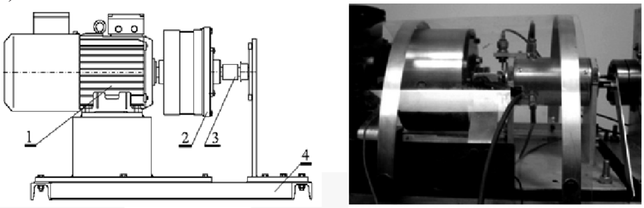



Fig. 4. Scheme of the test rig for testing the durability of cylindrical viscous brake; a) construction scheme: 1 – controlled electric motor, 2 – tested brake, 3 – torque meter, 4 – test rig frame; b) general view

After the test rig was started, for both liquid at time *t*, given in Table 2, a significant increase in the value of the transmitted torque showing the brake damage was noticed.

Table 2

**Test conditions and results of cylinder viscous brake**

| Fluid symbol | w [rad/s] | M [N×m] | T [°C] | t [hour] | S [J/cm$^3$] |
|---|---|---|---|---|---|
| LID 3354S | 50 | 1.9 | 40–50 | 70 | $1.7\times10^5$ |
| CES35 | 50 | 0.9 | 40–50 | 55 | $0.6\times10^5$ |

After the brake has been disassembled, in both cases, the presence of solid particles in the electrorheological fluid, in the bearings and on the sealing ring inner surfaces has been noticed, Fig. 5.

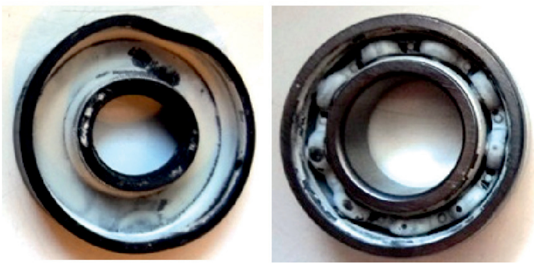


Fig. 5. View of solid particles in the electrorheological fluid in bearings and on the sealing ring inner surfaces

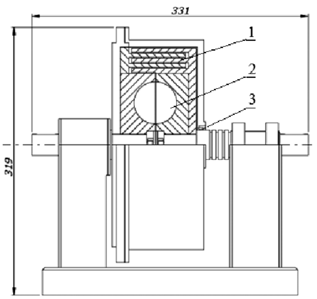
The reason of a significant increase of the brake torque values was rolling of solid particles included in the electrorheological fluid through ball bearings on bearing ring tracks and the formation of a layer, which obviates the clearance between bearing elements. It caused an increase of the resistance movement.

No adverse chemical impact of the fluid on the material of the sealing ring was observed. The cylinder surface became dull and there were no pits or scratches. Under the microscope, no significant changes in the size and shape of solid particles were noticed in the fluid taken from the brake. During the studies with rheometer, there were no significant changes noticed in the coefficient of dynamic viscosity of the two fluids.

**B. Dual clutch durability test**

A dual clutch consists of a hydrokinetic clutch and a viscous clutch cylinder located in a common housing [27]. The torque *M* transmitted by the dual clutch is the sum of moments carried by the hydrokinetic and viscous clutches. Rotors of the hydrokinetic clutch have flat radial blades. A viscous clutch is made of co-axial cylinders, isolated from each other. The driving and driven parts of the clutch as well as the housing are made from standard steel. The electric field acting on the electrorheological working fluid is produced in the gap between the cylinders with a width of 1 mm. The brake external diameter is 250 mm and its width is 110 mm. Fig. 6 shows a sectional view of the dual clutch.

a)




b)

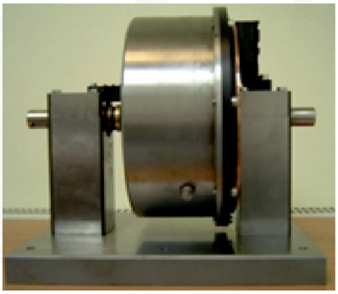


Fig. 6. Dual clutch: a) construction scheme, b) general view

The input and output shafts of the dual clutch are located outside the housing. The housing is sealed with the sealing ring mounted on the clutch output shaft. The voltage necessary to generate an electric field is applied to the cylinders through a copper-carbon brushes cooperating with the copper rings arranged on the output shaft of the clutch. Coupling complex was filled with the electrorheological fluid, whose data are shown in Table 3. The dual clutch was installed on the testy rig that enables the measurement of the angular velocity ω and the transmitted torque *M*, Fig. 7. During the research, the driving part of the clutch rotated with a speed of 100 rad/*s*, and the voltage of 1 kV was adjusted to the dual clutch cylinders.

Table 3

Basic data of the liquid used in the dual clutch [28]

| Fluid symbol LID 3354S | Smart Technology Ltd, UK [ 22] | Density [kg/m$^3$] | Fluid volumetric composition | Volume [cm$^3$] |
|---|---|---|---|---|
| ERF #6 | KCNiTCS Faculty of Chemistry, Warsaw University of Technology, PL | 1074 | 35% sulfonated resin styrene – divinylbenzene resin, silicone oil | 880 |

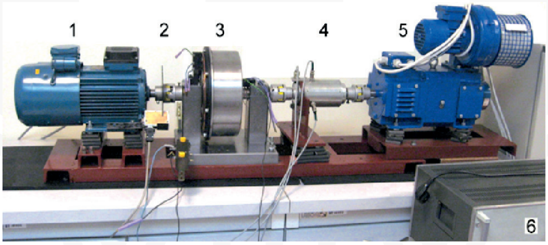



Fig. 7. View of the test bench with the installed dual clutch: 1 – electric motor, 2 – dual clutch, 3 – torque meter, 4 – electric brake, 5 – high voltage power supply

The electrorheological fluid ERF # 6 was working in the hydraulic dual clutch for 645 hours until the liquid leakage through the sealing ring was observed. After 600 hours, high voltage fluctuations were noticed. The fluctuations were caused by avalanche breakdowns. After the clutch was dismantled, the presence of solid particles of the electrorheological fluid on the inner surfaces of the sealing ring were observed as well as mechanical damage of the sealing surface, Fig. 8.

Fig. 8. The effects of the sealing ring wear

No adverse effects of the fluid chemical impact on the sealing ring material were observed. The cylinder surface was smooth, without pits or scratches; however, on the internal surfaces of the housing, corrosion was observed, Fig. 9.

As a result of observation under a scanning electron microscope, it was found consumption of solid spherical particles electrorheological fluid, such as flattening, damage the surface, adhesion of contaminants to the solid particles, Fig. 10.

Fig. 9. Corrosion spots inside the dual clutch housing

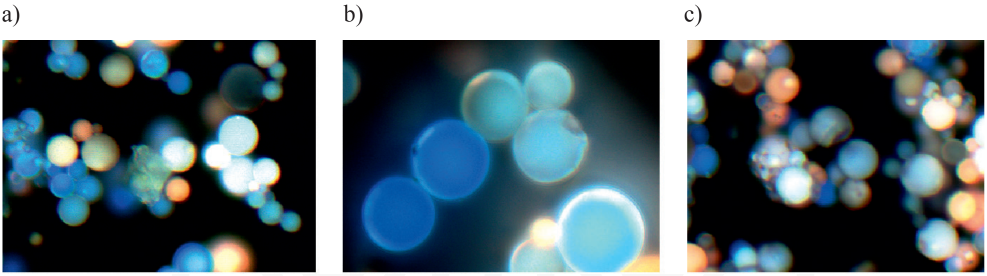


Fig. 10. Damage of the fluid solid particles ERF# 6 seen under UV light (365 nm), 400 times magnified: a) flattening of spherical solid particles, b) damage of the spherical particle surface damage, c) pollutants stuck to particles

However, the number of damaged particulates did not exceed a few percent, which indicates the beginning of the electrorheological fluid wear. Under the microscope, there was no evidence of silicone oil degradation, which is the electrorheological fluid liquid phase. During tests carried out on the rheometer, no significant changes in the coefficient of dynamic fluid viscosity ERF#6 were observed.

The value of the wear degree *S* of the electrorheological fluid working in the dual clutch, calculated on the basis of the formula (8) was $2.6 \times 105$ J/cm$^3$.

## 5. Evaluation of test results

As is clear from the research, the most important factor affecting the durability of viscous brake and dual clutch is the method of sealing the bearings and space with the electrorheological fluid. Also, the material of the electrorheological fluid particles is important. Particles made of a soft material are more easily deformed while rubbing against each other or against the cylinder walls, which is the reason of their easier passage through the seals. For this reason, the viscous brake filled with the fluid CES35, which consists of soft starch particles, crashed very quickly.

In order to increase the durability of devices filled with adaptive fuels, it is useful to put bearings outside of the housing. Although this design solution means the increase of the device size, it enables, according to the studies, the increase of the seal ring durability by nearly 10 times.

The observed degradation of solid particles of the fluid ERF# 6 are mainly associated with their movement inside the dual clutch housing. Particles moving between the viscous clutch cylinders and into the channel formed by the blades of the hydrodynamic clutch rub against the walls and against each other, and hit the blades during the flow of the electrorheological fluid from one hydrodynamic clutch rotor to another. The movement of solid particles is intensive, as it is apparent from the calculations for the angular speed of the clutch driving part, which is 100 rad/s, the flow velocity of the electrorheological fluid flow speed reach 5.5 m/s, and the maximum angles of impingement of the liquid stream on the blades reach the value of 55° [29]. The flatness of particles indicates the plastic properties of the material that they are made of. The reasons of pollution that has been observed in electrorheological fluids can be: corrosion and seal ring mechanical wear.

The type of used materials also influences the brake durability. As it is clear from the tests described in the paper, as well as the author's experience concerning devices filled with electrorheological fluid, aluminum is a better material for housing including adaptive fluids, because it does not corrode like a typical steel. The use of appropriate insulation materials ensures long and proper brake operation.

In order to achieve high durability of clutches and brakes filled with adaptive fluids, it is also necessary to provide adequate working conditions of devices. The most important factors are temperature and humidity. The device operating temperature results from the balance of heat supply and discharge. The amount of discharged heat into the environment is related to the brake size and the materials it was made of. The larger the brake and higher the thermal material conductivity, the lower is its working temperature. The temperature has a direct impact on electrorheological fluid properties and its destruction. In the case where the temperature increase causes shear stress $\tau$ increase, the power converted into heat in the device increases in the electrorheological fluid and consequently its durability decreases.

Ambient humidity has a significant impact on the durability because water percolating into the electrorheological fluid can cause degradation of fluid due to the electrolysis, as well as it can cause an increase in shear stress $\tau$, and also be the reason of corrosion of clutch or brake parts.

## 6. Conclusions

So far, the studies concerning the durability of devices filled with adaptive fluids have been performed for a small number of selected devices in specific working conditions, so the results do not provide a complete answer to questions on wear mechanisms of both their parts and adaptive fluids. Therefore, further experimental studies related to the durability of devices filled with adaptive fluids are necessary.

The experimental studies of the dual clutch and viscous brake, including three electrorheological fluids, show that the most important factors affecting the durability are: sealing of rolling bearings as well as working space filled with adaptive fluid, the type of adaptive fluid as well as the isolation of electrodes and electrical wires, supplying high voltage from the power supply. Electrorheological fluid durability, defined by means of the wear degree *S,* is within the ranges reported in the literature and does not differ significantly from the magnetorheological fluid durability.

Due to the presence of solid particles in adaptive fluids, it is necessary to use sealing rings adapted to work with mixtures containing particles. While selecting sealing rings, the impact of chemical ingredients of the electrorheological fluid on the material the ring has been made of should also be taken into account.

The durability of the electrorheological fluid solid particles is less than the silicone oil durability. The basic forms of particle mechanical wear include both surface flattening and damage. However, crushing of solid particles included in the electrorheological fluid, characteristic for linear dampers, which causes the large increase of dynamic viscous coefficient for the inactive electrorheological fluid, has not been observed.

## References


[1] Papadopoulos C.A., *Brakes and Clutches Using ER Fluids*, Mechatronics 8, 1998, 719–26.

[2] Li H.W, Du H., *Design and Experimental Evolution of a Magnetoreological Brake*, Int. J. Adv. Manuf. Technol, 21, 2003, 508–515.

[3] Stevens N., Sproston J., Stanway R., A*n Experimental Study of Electro–rheological Torque Transmission*, Transaction of the ASWE, Vol. 110, June 1988, 182–188.

[4] Kesy Z., *Prospects for the Control of a Torque Converter Using Magnetic Fluid*, International Colloquium – Innovative Actuators for Mechatronic Systems, Londyn 1995, 10.1–10.3 2.

[5] Conrad H., E*lectrorheological Fluids: Characteristics, Structure and Mechanisms*, FED–Vol. 164, Electro-Rheological Flow, ASME, 1993, 99–113.

[6] Stanway R., *Smart Fluids: Current and Future Developments*, Material Sciences and Technology, Vol. 20, 2004, 931–939.

[7] Weiss D. et al., *High Strength Magneto- and Electro-Rheological Fluids*, SAE Technical Paper 932451, 1993, 425–430.

[8] Fertman V.E., *Magnetic Fluids Guide Book: Properties and Applications*, Hemisphere Publishing Corporation, 1990.

[9] Nakamura T., Saga N., Nakazawa M., *Impedance Control of a One Shaft-Type Clutch Using Homogeneous Electrorheological Fluid*, Journal of Intelligent Material Systems and Structures, Vol. 13, No. 7–8, 2002, 465–469.

[10] Inoue A, Ryu U., Nishimura S., *Caster-walker with Intelligent Brakes Employing ER Fluid Composed of Liquid Crystalline Polysiloxane*, Proceedings of the Eighth International Conference on Electrorheological Fluids and Magnetorheological Suspensions, Nice, France 9–13 July 2001, World Scientific Publishing Co. 2002, 23–29.

[11] Kesy Z., Kesy A., Rudnicki J., *An Experimental Study of Controlled Breaker with Magneto-Rheological Working Fluid*, [in:] R.M. Parkin, A. Alhaibeh, M.R. Jackson (Ed.), International Conference on Mechatronics ICOM 2003, Professional Engineering Publishing Limited, London 2003, 321– 326.

[12] Kesy Z., Kesy A., Plocharski J., Jackson M., Parkin R., *An Example of Design – Embodiment for Electrorheological Fluid Based Mechatronic Transmission Components*, International Journal of Mechatronics 16 (1), 2006, 33–39.

[13] Park E.J., da Luz L.F. Suleman A., *Multidisciplinary Design Optimization of an Automotive Magnetoreological Brake Design*, Computers and Structures, 2007.
[14] Smith A.L., Ulicny J.C., Kennedy L.C., *Magnetorheological Fluid Fan Drive for Trucks*, Journal of Intelligent Material Systems and Structures, Vol. 18, No. 12/2007, 1131–1136.
[15] Sztompka P., Krzton-Maziopa, Plocharski J., *Electrochemical and Thermal Degradation of Electrorheological Fluids*, International Conference ERMR, Philadelphia 2010.
[16] Gurka M., Adams D., Johnston L., Petricevic R., *New Electrorheological Fluids – Characteristics and Implementation in Industrial and Mobile Applications*, 11th Conference on Electrorheological Fluids and Magnetorheological Suspensions, Journal of Physics: Conference Series 149, 2009.
[17] Carlson J.D., *What Makes a Good MR Fluid?*. 8th International Conference on Electrorheological Fluids and Magnetorheological Suspensions, July 9–13, Nice 2001.
[18] Juncheol Jeon, Sung Hoon Ha, Min-Sang Seong, Seung-Bok Choi,Young-Min Han, *Wear Characteristics of Electrorheological Fluids with Different Base Oil and Particle Concentration*, International Journal of Civil Engineering and Building Materials, Vol. 1, No. 1, 2011.
[19] Iyengar V.R., Alexandridis A.A., Tung S.C., Rule D.S., *Wear Testing of Seals in Magneto-Rheological Fluids*, Tribology Transactions, 47:1, 2004, 23–28.
[20] Carlson D.J., *MR Fluids and Devices in the Real World*, 9th International Conference on Electro-Rheological Fluids, Magneto-Rheological Suspensions and Associated Technology, Beijing 2004, 531–538.
[21] Whorlow R.W., *Rheological Techniques*, Second Edition, Ellis Horwood Limited, 1992.
[22] www.smarttec.co.uk.
[23] Gene S., Phule P., *Rheological Properties of Magnetorheological Fluids*, Smart Materials and Stuctures 11, 2002, 140–146.
[24] Carlson J.D., *Magnetorheological Fluid Actuators*, Chapter on Magnetorheological Fluid Actuators in Adaptronics and Smart Structures, Jendritza D.J., Janocha H., Springer Verlag, 1997.
[25] Kesy Z., Kesy A., Olszak A., Jackson M., Parkin R., *Modelling of Unsteady-state Motion of Transmission System with Electrically Controlled Viscotic Clutch*, Proc 5$^{th}$ Internation Workashop on Research and Education in Mechatronics, Kielce–Cedzyna 2004, 223–227.
[26] Kesy Z., Kesy A., Jackson M.R., Parkin R.M., *Investigation of Viscotic Clutch with Electrorheological Fluid*, International Review of Mechanical Engineering, Vol. 2, No. 4, 2008, 592 – 597, .
[27] Ziabska E., Musialek I., Olszak A., Kesy Z., *Durability Assessment of Elektroreological Fluids*, Hydraulics and Pneumatics 3/2013, 8–11 (in Polish).
[28] Plocharski J, Drabik H., Wycislik H., Ciach T., *Electrorheological Properties of Polyphenylene Suspensions*, Synthetic Metals 88, 1997, 139–145.
[29] Ziabska E., Olszak A., Kesy Z., *B-spline Application in Calculation of Hydrodynamic Torque Converters with Electrrheological Fluids*, Mechanic, No. 12, 2013, 43–50 (in Polish).