KAUNAS UNIVERSITY OF TECHNOLOGY
VYTAUTAS MAGNUS UNIVERSITY

JORIS VĖŽYS

DEVELOPMENT OF THE DEVICE FOR THE RESEARCH OF MAGNETORHEOLOGICAL FLUIDS PROPERTIES

Summary of Doctoral Dissertation
Technological Sciences, Mechanical Engineering (T 009)

2019, Kaunas

This doctoral dissertation was prepared at Kaunas University of Technology, Faculty of Mechanical Engineering and Design, Department of Manufacturing Engineering during the period of 2014–2018.

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Editor: B.Brasienė (Publishing house "Technologija")

Dissertation Defence Board of Mechanical Engineering Science Field:
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Summary of the doctoral dissertation was sent on 14 May, 2019.
The doctoral dissertation is available on the internet http://ktu.edu and at the libraries of Kaunas University of Technology (K. Donelaičio St. 20, 44239 Kaunas, Lithuania) and Vytautas Magnus University Agriculture Academy (Studentų St. 11, Akademija, 53361 Kauno raj., Lithuania).

KAUNO TECHNOLOGIJOS UNIVERSITETAS
VYTAUTO DIDŽIOJO UNIVERSITETAS

JORIS VĖŽYS

ĮRENGINIO MAGNETOREOLOGINIŲ SKYSČIŲ SAVYBIŲ TYRIMUI KŪRIMAS

Daktaro disertacijos santrauka
Technologijos mokslai, mechanikos inžinerija (T 009)

2019, Kaunas

Disertacija rengta 2014-2018 metais Kauno technologijos universiteto Mechanikos inžinerijos ir dizaino fakultete Gamybos inžinerijos katedroje.

Mokslinis vadovas:
Prof., dr. Egidijus DRAGAŠIUS (Kauno technologijos universitetas, Gamybos inžinerijos katedra – T 009).

Redagavo: B.Brasienė (leidykla „Technologija“)

Mechanikos inžinerijos mokslo krypties disertacijos gynimo taryba:
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Disertacija bus ginama viešame mechanikos inžinerijos mokslo krypties disertacijos gynimo tarybos posėdyje 2019 m. birželio 14 d. 12 val. Kauno technologijos universiteto disertacijų gynimo salėje.

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INTRODUCTION

Relevance of the topic

Many smart materials are currently being invented. One of the groups of smart materials is smart fluids. The main fluids in this group are electrorheological and magnetorheological. These modern fluids are increasingly used in a wide variety of fields, such as medicine, military industry, automotive industry, aviation, etc. It is easier to control electrorheological fluids in comparison to the magnetorheological ones, because of the high electrical voltages that are sufficient for the electrorheological fluids. However, electrorheological fluids have some significant drawbacks as well. Their shear stresses are lower than in the magnetorheological fluids.

Magnetorheological fluids belong to a group of smart fluids. These fluids are controlled by a magnetic field and can change their state from fluid to solid and vice versa in just a few milliseconds. Moreover, such fluids are widely used and investigated in Lithuania, where professors Ramutis Petras Bansevičius, Egidijus Dragašius and other KTU scientists are involved. A number of scientists have carried out a research at the Belarusian A.V. Luykov Institute of Heat and Mass Exchange as well; MR fluids of different modifications are created there and applied in real mechanisms such as shock absorbers. However, magnetorheological fluids have some drawbacks as well: their high cost (about $ 1,000 per 1 litre) limits their availability; the stability (sedimentation) of these fluids is a major problem as well. In a device that works with magnetorheological fluids, it may be a critical parameter, as particles in the unused mechanism will settle for traction. When the mechanism is activated, and the MR fluid is affected by the magnetic field, this may not work properly, because the particles will settle at the bottom, and the carrier fluid will be at the top. Scientists have been trying to solve the problem of particle deposition for a long time. For this reason, certain impurities are used in the carrier fluid. It is as well possible to add nano particles, slowing down the sedimentation process. One of the largest magnetorheological fluid manufacturers in the USA is LORD. It is written on its website [54] that the sedimentation of particles that they produce practically does not exist. However, in this work, two magnetorheological fluids that are produced by their company are investigated, and the sedimentation can be visualized after about 24 hours. Moreover, after 2 weeks, the particles in the magnetorheological fluids are already completely settled.

There are several ways to detect sedimentation in magnetorheological fluids. e.g. by using an ultrasound, X-rays, detecting temperature change, measuring how the coil inductance changes, etc. This paper introduces a new method of

determining sedimentation that has not been used anywhere else by measuring the electrical resistivity of the fluid. This method is registered within the Lithuanian Patent Office and is pending for its approval.
During this work, 5 different magnetorheological fluids were investigated. An autonomous sedimentation unit with particle mixing function was developed as well. This device determines the degree of sedimentation in a magnetorheological fluid and can be mounted on most of the mechanisms that work with magnetorheological fluids. It is expected that in the future, such devices will solve the problem of instability of magnetorheological fluids, and all mechanisms will work properly.

Aim and tasks of the work

The aim of this dissertation is to create a device for determining the degree of magnetorheological fluid (MR) sedimentation in mechanisms that work with MR fluids and to mix the fluid to maintain its performance.

Tasks to achieve this aim are as follows:

1. Perform the analysis of literature and patent material in aspects of research, monitoring and conditioning of the magnetorheological fluids.
2. Create a mathematical model to describe the sedimentation process of particles. Describe the influence of harmonic oscillations for sedimentation process. Theoretically derive the equation of resistivity dependence on the level of sedimentation R = f (S). Compare the experimental and theoretical results.
3. Perform a research on different MR fluids by using rheometer to obtain the shear stress dependence on the shear rate with and without the action of magnetic field.
4. Develop a method to determine the level of sedimentation in MR fluids and a method to mix the fluid, create special sensors to determine the electrical resistivity in the MR fluid under the magnetic field and verify this new method experimentally.
5. Develop a device to determine the level of sedimentation in MR fluids and automatically mix the fluid.

Methods and equipment

The dissertation was based on theoretical, analytical and experimental research. Three special sensors for measuring electrical resistance were developed for the experimental research. The MR mechanism has been improved by adapting the resistance measurement sensors to determine the degree of sedimentation and applying piezoelectric actuators for mixing the MR fluid.

Scientific novelty

- Sedimentation process in the magnetorheological fluid was mathematically described; forces, which affect particles that are using harmonic oscillations, were determined.
- A new method to determine the sedimentation level in the MR fluids, measuring its electric resistivity under the magnetic field, was developed.
- Sensors to determine the electrical resistivity in the MR fluid were created.
- Piezo actuators, working in resonance frequency, were used to mix the settled MR fluid.
- Original construction automatic device to determine the sedimentation level in the MR fluid and to mix it was designed and created.

Practical value

The MR fluid measurement and monitoring system for measuring and monitoring the sedimentation phenomenon are designed. For the determination of the degree of sedimentation, the newly developed method for measuring the electrical resistance of the fluid was used. Piezoelectric actuators are used for fluid mixing, which determine their resonant frequency by feedback, which helps to mix the settled fluid more efficiently. The degree of sedimentation is measured autonomously with the built-in device, and the measured results are recorded on a microSD card and can then be analysed.

Work results provided for the defence

1. A mathematical model for describing the sedimentation of magnetoreological fluid particles and the forces acting on these particles in harmonic vibrations were developed.
2. A mathematical expression that allows the assessment of the electrical resistance dependence of the MR fluid on the magnetic field from the degree of sedimentation was derived.
3. Five different MR fluids were analysed by using a rheometer, and the parameter analysis was performed.
4. A method for determining the degree of sedimentation in the MR fluid is created by measuring the electrical resistance of the fluid, exposed to the magnetic field.

5. Three special MRS electrical resistance measurement sensors have been developed for the resistance measurement.
6. Two different methods of sedimentation detection in the magnetorheological fluids were analysed and compared.
7. The dependence of the braking torque of magnetorheological brake on the degree of magnetorheological fluid sedimentation was established.
8. The modified MR brake construction is designed to determine the degree of sedimentation and to mix the fluid inside.
9. A functioning device for the sedimentation degree mechanism with MR setting has been developed and produced.

Approval of the work

The scientific results were presented in 3 publications in the ISI Database of the Institute of Scientific Information, with citation index, as well as at 3 international scientific conferences. An application for the scientific invention of the Republic of Lithuania patent has been published.

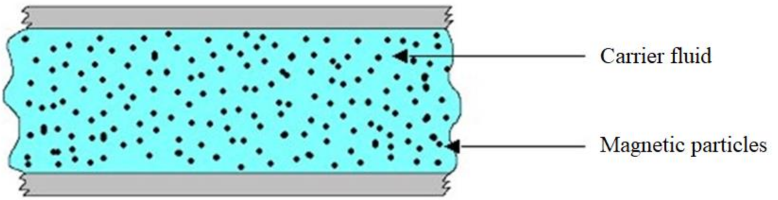
Used words and phrases

MRS – magnetorehological fluids
MR – magnetorheological
PE – pjezoelectric

1. ANALYSIS OF LITERATURE

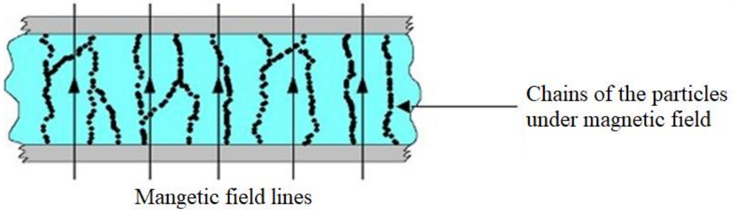
Active materials that can be controlled in a variable magnetic field are magnetorheological (MR) and ferromagnetic fluids [1]. These fluids are usually composed of iron particles and carrier liquid [2]. When these fluids are affected by the magnetic field, they change their state from liquid to solid [3]. Therefore, the change of magnetic field strength can actively change the viscosity of fluids [4]. Magnetic fluid viscosity control requires an electromagnet that, unlike a permanent magnet, allows better control of the viscosity of these fluids. Magnetoreological fluid differs from ferromagnetic fluid due to the particle sizes. The particles of ferromagnetic fluid are smaller, nanometer-sized (~ 10 nm). The particles of the magnetoreological fluid are larger, in the scale of micrometres (3‒10 μm) [5]; thus, this fluid's density is higher, and the movement of particles does not occur, according to Brown's law [6]. For this reason, when the MR fluid is affected by the magnetic field, the fluid particles can be arranged among the magnetic lines in the field. The particles of the ferromagnetic fluid are queues of nanometers [7], thus, this fluid remains lower in density and retains the movement of particles, according to Brown's law. In this case, when the magnetic field is exposed to the magnetic fluid, the particle-carrying fluid cannot be stopped between the particles that are bound in the magnetic field. These properties make these two magnetic fluids different [8].

As mentioned above, the MR fluid is comprised of a micrometer-sized array of magnetic particles. In their form, they are usually spheres or ellipses [9]. These particles are mixed with carrier liquid (water, oil, glycol or liquid with similar properties). When the MR fluid is not exposed to the magnetic field, these particles can float freely in the carrier fluid. The MR fluid that is not affected by the magnetic field is shown (Figure 1.1).



1.1 Figure. Magnetoreological fluid not affected by the magnetic field [10]

When the magnetic field affects the MR fluid, the microscopic particle size (0.1–10 μm) acquires a bipolar magnetic moment and interacts with each other by being aligned with the magnetic field (Figure 1.2). Since this fluid is between two magnetic poles (northern and southern), the adhesive particles form compounds of 0.5–2 mm size, which are constrained by the magnetic field force that is being created. These magnetic particle compounds prevent the carrier fluid from flowing easily. For these reasons, the viscosity of MR fluid in the magnetic field increases.



1.2 Figure. MR fluid affected by the magnetic field [10]

When the magnetic field is interrupted, there is no residual magnetic brake force; thus, the carrier fluid is not stopped. The MR fluid again becomes the same viscosity and the same properties as before being exposed to the magnetic field [10].

Since the magnetic field is affected by MR, the fluid may change its state from liquid to quasi-solid, and after the magnetic field stops, it returns to its original state. Therefore, the magnetorheological fluid, exposed to the magnetic field, acquires the following properties, which are assimilated to the solid bodies: shear, tension, etc. However, the stresses in this fluid depend on the strength of the magnetic field that is acting on it [11]. This value depends on the density of the magnetic field, at which the magnetic saturation occurs. During this phenomenon, the magnetic field density begins to change; thus, the state of the magnetorheological fluid is described by using the Bigham plasticity function, taking into account the properties of the material that is being calculated. However, the characteristics of the MR fluid are usually not fully consistent with the calculated Bighamo plasticity function. For example, when exposed to low magnetic field stresses, while the MR fluid is exposed to a weak magnetic field, it acts as a viscoelastic material under complex modules that depend on the intensity of the magnetic field. Therefore, the viscosity of such an MR fluid can be calculated by shear functions, where the MR fluid is subjected to magnetic field changes in shear size. This size depends on the viscosity of the MR fluid.

2. MATHEMATICAL MODELING OF MAGNETOREOLOGICAL FLUID SEDIMENTATION

In this case, the mathematically described particle movement in MR fluid is when they are in the middle of the containing tube or near the wall. It has been found that the particle is closer to the wall of the stationary tube; thus, its speed is lower due to the friction forces. There is as well a mathematical model where the infinite band of an unlimited length of one particle is turned by harmonic vibrations. The stationary and dynamic components of the tangential force that are formed by the vibration of the fluid are described. The first two approximations are described to get the most accurate results. These forces were calculated for all five fluids that were later experimentally investigated. Later, the experiments will be attempted to validate the created mathematical model. Since it is not possible to determine the sedimentation of particles in the MR fluid directly, an indirect method will be chosen by measuring the magnetic resistance of the MR field that is affected by the magnetic field. There is as well a theory of backflow force, which is small, but must be generated in the fluid by sitting and pushing the carrier fluid underneath. This fluid at the bottom of the vessel strikes the bottom of the vessel and creates the opposite force to the seat.

Moreover, when combining two theories, i.e., resistance to the magnetic field and determination of the degree of sedimentation, the formula of the degree of resistance to sedimentation has been derived. It shows how the resistance changes when the particles are in the fluid and sedimentation occurs.

2.1. Smooth movement of fluid longitudinal strips on the wall

In order to find out more details about the processes that are occurring in the fluid particles boarding magnetoreologiniame created a mathematical model, describing the particle sedimentation process. By simplifying the model, the particle size of one particle in the x and y plane and the unlimited length z in the thin stripe are taken (Figure 2.1). The movement of this stripe as it moves down smoothly is described. It as well evaluates how the particle velocity changes when approaching a stationary vessel containing MR fluid. Since the particle deposition process is completely halted, the reaction of the infinite particle band to the harmonic oscillations is mathematically described, trying to keep them in the fluid and prevent them from settling. Moreover, the back movement of the fluid inside the tube is described.

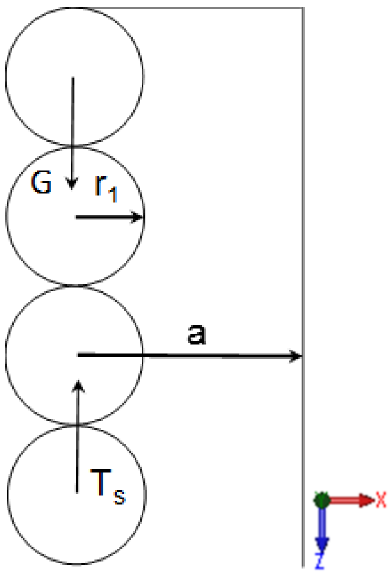


Figure 2.1. The principal scheme of the model

This moving cylinder is considered to be inside another larger and more stationary beam cylinder. The marginal conditions can be described as follows:

$$\begin{cases} v(r_1) = U + b\omega\cos\omega t, \\ v(r_2) = 0. \end{cases} \quad (1.1).$$

It is regarded that the fluid between the cylinders is viscous non-stick. Suppose that the velocities of the fluid particles are parallel to the z axis, and the pressure gradient in the z axis is zero:

$$v_r = v_\varphi = 0, \quad \frac{\partial p}{\partial z} = 0, \quad v_z = v(r,t) \quad (1.2).$$

The fluid dynamics equation is described in the cylindrical coordinates r, φ, z :

$$\frac{\partial v}{\partial t} = \nu_s \left(\frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r} \right) \quad (1.3).$$

The fluid particle velocity after the evaluation of all boundary conditions can be requested as follows:

$$v(r,t) = U\frac{\ln r - \ln r_2}{\ln r_1 - \ln r_2} + b\omega\frac{A(r)\cos\omega t - B(r)\sin\omega t}{c_1} \quad (1.4).$$

The tension on the cylinder surface due to the viscous fluid is $p_{rz} = \mu\frac{\partial v}{\partial r}$; thus, the total force in the z direction length of the cylinder unit is as follows:

$$T = 2\pi r_1 p_{rz} = 2\pi\mu r_1\frac{\partial v}{\partial r} \quad (1.5).$$

2.2. Determination of sedimentation in the magnetoreological fluids by measuring their electrical resistance

In order to get an equation for the resistivity dependence on sedimentation *R = f (S)*, the magnetization of particles in the magnetorheological fluid can be written as follows:

$$M = \rho_p \cdot m \cdot L(\xi) \quad (1.6);$$

where $$L(\xi) = 1 - \frac{1}{\xi} \quad (1.7).$$

L is Langevin function. ξ can be expressed as follows:

$$\xi = \frac{\pi}{6}\frac{\mu_o M_s a^3 H}{kT} \quad (1.8).$$

The magnetization of two particles in magnetorheological fluid can be written as:

$$M = M_s\left(1 - \frac{6kT}{\pi\mu_o M_s a^3 H}\right) = M_s \cdot \left(1 - \frac{1}{\xi}\right) \quad (1.9),$$

$$M_s = \rho_p \cdot m$$

where: (1.10),

$$\rho_p = \frac{M_s}{m} \quad (1.11).$$

Motion equation of two dipoles in the magnetorheological fluid can be expressed as follows:

$$\frac{\pi}{6}a^3\rho\frac{d^2x}{dt^2} + 3\pi\eta a\frac{dx}{dt} + \frac{\pi}{6}\mu_o a^3 M\delta = 0 \quad (1.12).$$

The solution of this equation is as follows:

$$x = x_{max} - \frac{kT\xi}{3\pi a\eta H} \quad (1.13).$$

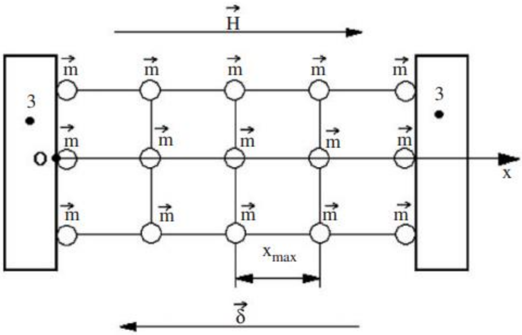


Figure 2.2. The iron microparticles, aligned at the initial moment with the direction of the magnetic field lines: H – magnetic field intensity; δ – magnetic field gradient; m – dipolar magnetic moment; 3 – non-magnetic electrodes

By using the solution of equation number 1.12, the equivalent electric resistivity between plates that are placed in magnetorheological fluid can be expressed as follows:

$$R = \frac{2\rho_m}{3\pi\varphi a l}\left(x_{max} - \frac{\mu_0 M_s}{18\eta}\delta a^2 t\right) \qquad (1.14).$$

By using Sotke's law, the velocity of sedimentation can be written as follows:

$$v_s = \frac{2}{9}\frac{(\rho_p - \rho_t)}{\eta} g a^2 \qquad (1.15).$$

The coefficient of sedimentation can be written as follows:

$$s = \frac{v_s}{g} = \frac{2}{9}\frac{(\rho_p - \rho_t)}{\eta} a^2 \qquad (1.16).$$

By using the definition of magnetic particle density from equation number 2, the following equation is perceived:

$$s = \frac{v_s}{g} = \frac{2}{9}\frac{\left(\frac{M_s}{m} - \rho_t\right)}{\eta} a^2 \qquad (1.17).$$

From the equation number 10, the value of M_s could be expressed:

$$M_s = m \cdot \left(\rho_t + \frac{9S\eta}{2a^2}\right) = \frac{9S\eta m}{2a^2} + \rho_t m \quad (1.18).$$

Putting this equation to the equation number 1.14, the resistivity dependence on sedimentation is perceived:

$$R = R(S) = \frac{2\rho_m x_{max}}{3\pi l \varphi a} - \frac{\rho_m \mu_0 m \cdot (2a^2\rho_t + 9S\eta)}{54\pi l \eta a^2} a\delta t \quad (1.19).$$

In this part, some marks are given. There are the definitions of the most of them:

η – MRF viscosity, g – free fall acceleration, ρ_t – carrier fluid density, ρ_m – MRF resistance when H = 0, φ – volume of the microparticles, l – diameter of the electrodes, ρ_p – magnetic particle density, m – dipole magnetic moment, μ_0 – magnetic permeability of the vacuum, M_S – saturated magnetization, a – radius of micro particles, H – magnetic field strength, kT – thermal energy.

2.3. Comparison of experimental and theoretical results

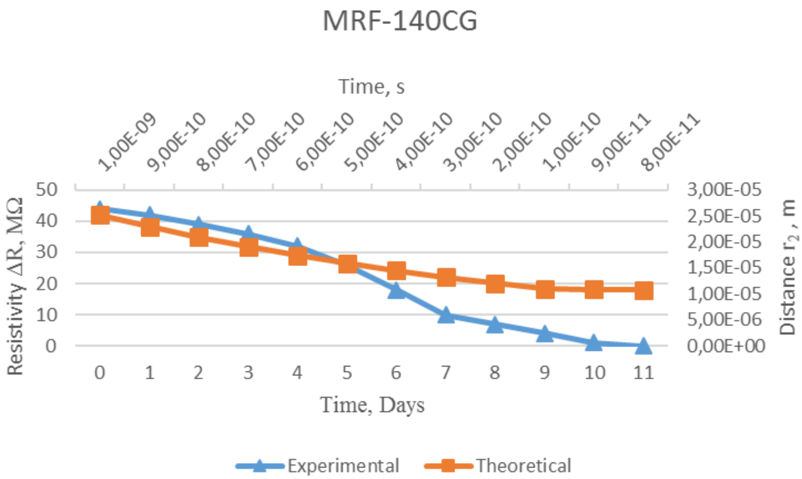
The coefficient of sedimentation can be written as follows:

$$S = \frac{U}{g} = \frac{\rho_m - \rho_v}{2\mu} \cdot r_1^2 \cdot \ln\left(\frac{r_2}{r_1}\right) \quad (1.20).$$

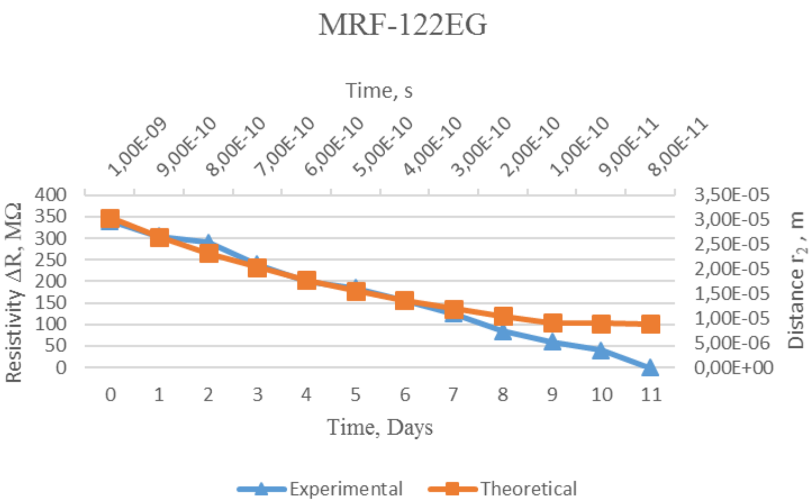
Since the distance r_2 is between the particles, it could be said that the lower is r_2, the greater is the concentration of particles. The distance dependence on sedimentation speed is as follows:

$$r_2 = e^{\left(\frac{2\mu}{(\rho_m - \rho_v) r_1^2} S\right)} \cdot r_1 \quad (1.21).$$

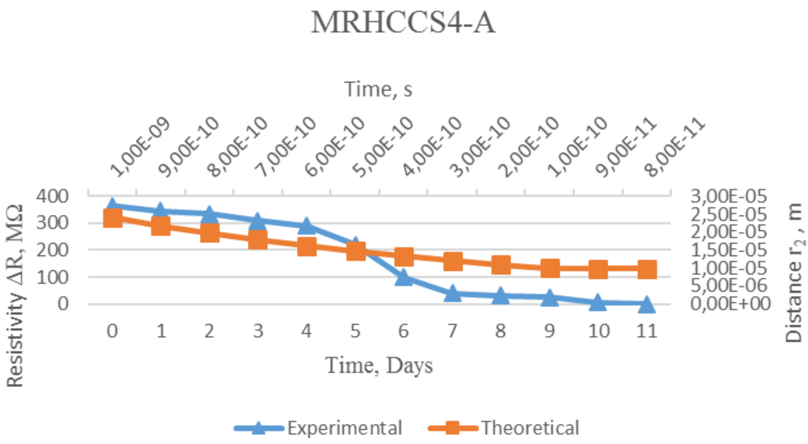
The mathematical model that was developed in this work only works when there is selected a very small r_2 ($10^{-6} - 10^{-5}$m) and sedimentation time ($10^{-9} - 10^{-11}$s). The sedimentation time dependency S from distance graphs for all five magnetoreological fluids is studied later (Figure 2.3).


MRF-140CG
Time, s
1,00E-09
9,00E-10
8,00E-10
7,00E-10
6,00E-10
5,00E-10
4,00E-10
3,00E-10
2,00E-10
1,00E-10
9,00E-11
8,00E-11
Resistivity ΔR, MΩ
50
40
30
20
10
0
3,00E-05
2,50E-05
2,00E-05
1,50E-05
1,00E-05
5,00E-06
0,00E+00
Distance r2 , m
0 1 2 3 4 5 6 7 8 9 10 11
Time, Days
Experimental
Theoretical

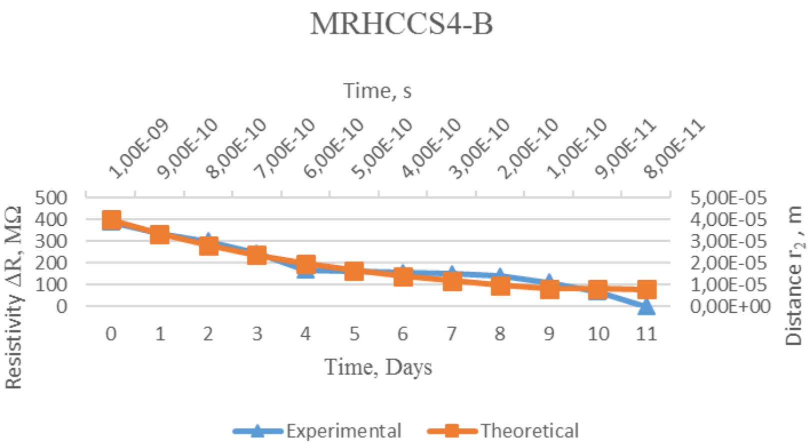
a


MRF-122EG
Time, s
1,00E-09
9,00E-10
8,00E-10
7,00E-10
6,00E-10
5,00E-10
4,00E-10
3,00E-10
2,00E-10
1,00E-10
9,00E-11
8,00E-11
Resistivity ΔR, MΩ
400
350
300
250
200
150
100
50
0
3,50E-05
3,00E-05
2,50E-05
2,00E-05
1,50E-05
1,00E-05
5,00E-06
0,00E+00
Distance r2 , m
0 1 2 3 4 5 6 7 8 9 10 11
Time, Days
Experimental
Theoretical

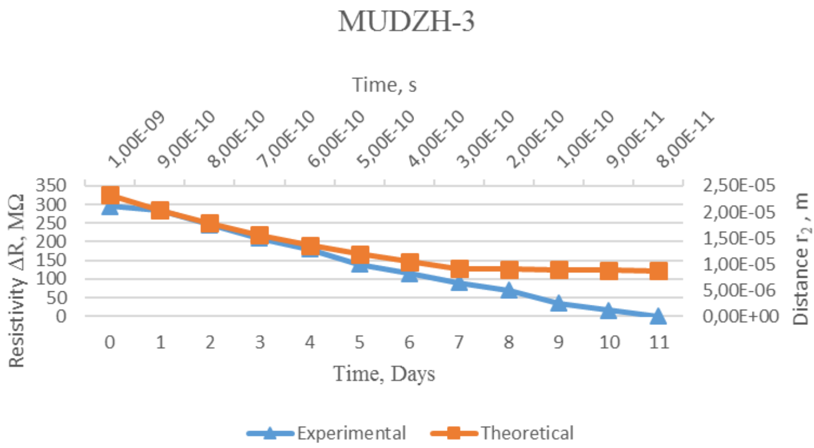
b


MRHCCS4-A
Time, s
1,00E-09
9,00E-10
8,00E-10
7,00E-10
6,00E-10
5,00E-10
4,00E-10
3,00E-10
2,00E-10
1,00E-10
9,00E-11
8,00E-11
Resistivity ΔR, MΩ
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11
Time, Days
3,00E-05
2,50E-05
2,00E-05
1,50E-05
1,00E-05
5,00E-06
0,00E+00
Distance r2 , m
Experimental
Theoretical

c


MRHCCS4-B
Time, s
1,00E-09
9,00E-10
8,00E-10
7,00E-10
6,00E-10
5,00E-10
4,00E-10
3,00E-10
2,00E-10
1,00E-10
9,00E-11
8,00E-11
Resistivity ΔR, MΩ
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11
Time, Days
5,00E-05
4,00E-05
3,00E-05
2,00E-05
1,00E-05
0,00E+00
Distance r2 , m
Experimental
Theoretical

d



e

Figure 2.3. Experimentally and theoretically obtained curves for different MR fluids: a – MRF-140CG, b – MRF-122EG, c – MRHCCS4-A, d – MRHCCS4-B, e – MUDZH-3

Since it was not possible to experimentally and directly measure the degree of sedimentation (concentration of particles in the fluid part of the fluid to be measured), the author of this dissertation chose an indirect method of measuring electrical resistance under the magnetic field of the fluid, described in the third chapter. The electrical resistance of the fully settled fluid was selected as the reference point (maximum resistance value). It was assumed that there is the highest particle concentration at this point, since practically all particles are deposited in the measured fluid spot. The change of resistance ΔR is obtained by subtracting the resistance, measured for a given number of days, from the resistance of each fully settled fluid. This results in indirect particle concentration (deposition). The change in the resistance of all five fluids to the time of sedimentation is depicted as well (Figure 2.3).

Although the theoretical and experimental values of the curves differ quite sharply, the curves are very similar in nature. The correlation coefficients for these fluids were obtained separately for each fluid. For the MRF-140CG, this factor is 0.970326, MRF-122EG - 0.970326, MRHCCS4-A - 0.953146, MRHCCS4-B - 0, 957598, MUDZH-3 - 0.954029. As it could be seen from the results, the theoretical calculations and experimental results depend on each other.

3. METHODOLOGY AND EXPERIMENTAL INVESTIGATION FOR DETERMINING SEDIMENTATION OF DIFFERENT MAGNETORHEOLOGICAL FLUIDS

This chapter attempts to validate the mathematical model experimentally. It includes five different fluid tests for the rheometer, the magnetization curve, the photomicroscope, and the development of the electrical resistance of the sensor. The experimental investigations of sedimentation were performed with this sensor by measuring the electrical resistance of the MR fluid under the magnetic field. The experimental determination of sedimentation by measuring coil inductance was performed.

The experimental testing of 5 different magnetoreological fluids: MRF-140CG and MRF-122EG, manufactured by Lord, USA, as well as produced by Liquids research company, UK, and magnetorheological fluid МУДЖ-3 from MRHCCS4-A and MRHCCS4-B, A.V. Luikov Institute of Heat and Mass Exchange, Minsk, Belarus. The concentrations of these fluid particles are given in Table 1.

Table 1. Particle concentration in different magnetoreological fluids

MR fluid	Concentration of particles	Manufacturer
MRF-140CG	85%	Lord, USA
MRF-122EG	72%	Lord, USA
MRHCCS4-A	70%	Liquids Research Limited, UK
MRHCCS4-B	80%	Liquids Research Limited, UK
MUDZH-3	71%	A.V. Luykov institute, BY

3.1. Experimental study of magnetoreological fluids with a rheometer

The shear stress (τ) dependence on shear rate was measured by a rheometer without magnetic field. The results are presented in Figure 3.1.

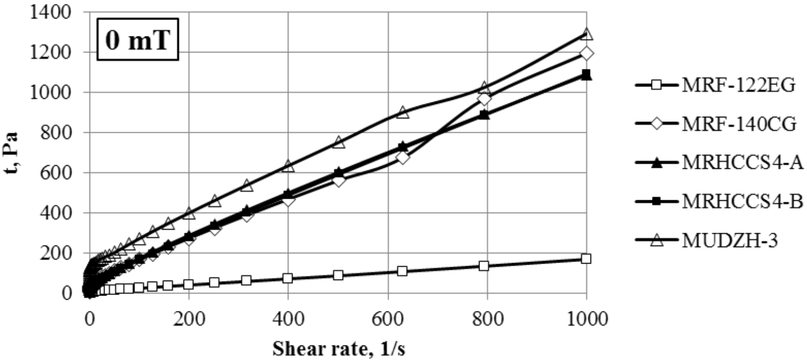


Figure 3.1. Shear stress dependence on shear rate without magnetic field

From the obtained dependencies, it could be seen that the highest shear stress under the magnetic field is MUDZH-3. The shear stress of both fluids, produced by Liquids Research, was practically the same. The magnetorological fluid MRF-122EG has a significantly lower shear stress than the other fluids. This could be due to the impurities that were contained in the fluid, and may be due to the concentration of its particles, as it is less than the fluid MRF-140CG, and the shear stress of this fluid is significantly higher. The shear stress of fluids when not in the magnetic field is a very important parameter when these fluids have to be used in real devices. It is best to use this fluid when the magnetorheological fluid shear stress under magnetic field is kept to a minimum, as this may affect the efficiency of the mechanism, acting on this fluid base. Ideally, the shear stress of a working magnetoreological fluid should be as low as possible when it is not in the magnetic field and as large as it is exposed to the magnetic field, but it is very difficult to achieve. In most cases, these are different fluids, adapted to the particular required mechanism. Moreover, the shear stress dependence of the shear rate was measured for the fluids under the 0–1 T magnetic field.

3.2. Magnetoreological fluid magnetization characteristics research

An experimental study was performed to obtain experimental curves of B - H (Figure 3.2) and J - H of three magnetoreological fluids. These characteristics of Lord's fluids are available online, as well as in Viktorija Mačiukienė's dissertation (Development and Research of Device for Determination of Magnetoreological Fluid Parameters). The experiment used magnetic properties measuring device with two Holo sensors. The essence of the halo phenomenon is that when a magnetic field is formed by the current conducting current, a magnetic field with a magnetic induction B perpendicular to the current density vector j causes a transverse electric field.

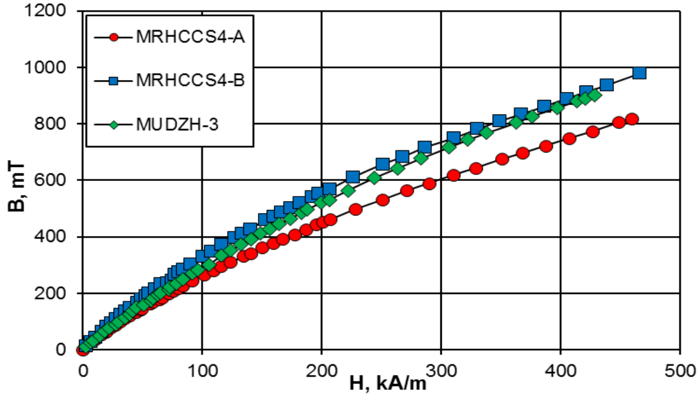


Figure 3.2. Experimental magnetoreological fluid B-H curve

Its strength vector EH is perpendicular to vectors j and B. The phenomenon is based on the interaction of moving electrical charges with the external magnetic field. When the electrical charge q moves at speed v in the magnetic field, it is triggered by the magnetic force of Lorenz.

3.3. Creating an electrical resistance measurement in magnetoreological fluids sensor

In order to determine the degree of sedimentation in magnetoreological fluids, the sensor has been developed that can measure the electrical resistance of the magnetoreal fluid that is affected by the magnetic field, which varies with the sedimentation of the particles.

A test bench was constructed to perform the tests (Figure 3.3). The tube 2 with the magnetoreological fluid was placed inside the coil 1, which gave a magnetic field after supplying the power supply 4. The fluid is immersed in a resistance measuring sensor 3, the contacts of which are connected to a mega-meter 5, which measures the resistance after the timer 6 has been set for 20 seconds from the timer.

Two different sensors were created for the experiment. In the first sensor, the electrodes were arranged in three positions to be measured at the top, middle and bottom of the vessel. The electrode distance is 1 mm. Another type of sensor has been designed to produce more accurate results. Its overall view is shown in Figure 3.4. The essence of this sensor is the wiping device 5. In order to move the sensor to another position, it is known that it really measures the resistance of the fluid in that place; this device was cleaned 5 times before the measurement. In order not to pull the sensor out of the fluid during the tests, both fluids are produced under the identical sensor.

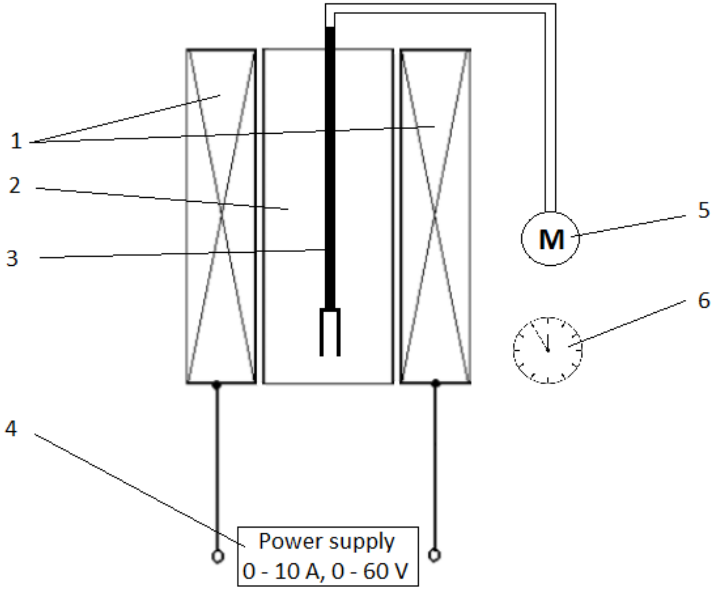


Figure. 3.3 Test stand: 1 - magnetic coil, 2 - MR tube with fluid, 3 - resistance measurement sensor, 4 - power supply, 5 - mega-meter, 6 - timer

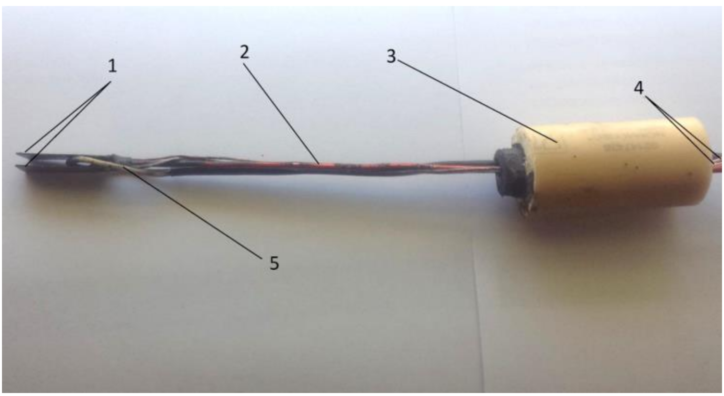


Figure. 3.4. Height-adjustable resistance sensor with plate cleaning device: 1 - contact plate, 2 - stand, 3 - plug, 4 - contact wire, 5 - plate cleaner

The resistance of both fluids was measured with these sensors. The measurements were made by mixing completely after one week and two weeks later. The dependence of the completely mixed magnetorological fluid MRF-140CG on the change of magnetic coil voltage is shown in Figure 3.5. Moreover, the MRF-122EG fluid was measured as well.

The magnetic field strength was adjusted by supplying different power supply voltage. The dependence of the magnetic field on the supply voltage is shown in Table 2.

Table 2. Magnetic field strength depending on voltages

U, V	5	10	15	20	25	30
B,A/m	7245	14491	21736	28982	36227	43473
U, V	35	40	45	50	55	60
B,A/m	50718	57964	65209	72454	79700	86945

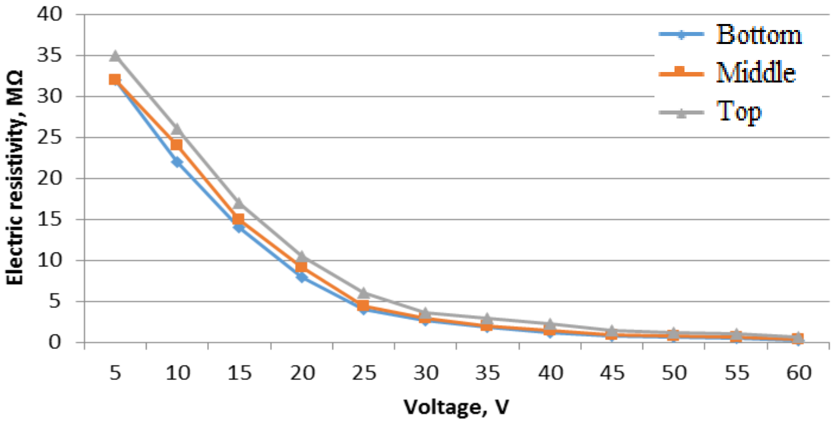


Figure. 3.5. Electrical resistance dependence on the supply voltage (magnetic field) when the mixed MRF-140CG fluid with a detergent cleaner is measured

After these tests, both magnetorheological fluids were left to settle. After a week and two weeks, the analogous measurements were made with the same sensors under the same conditions. MRF-140CG settled fluid resistivity dependence on the voltage is shown after one week in Figure 3.6.; after two weeks, it is shown in Figure 3.7.

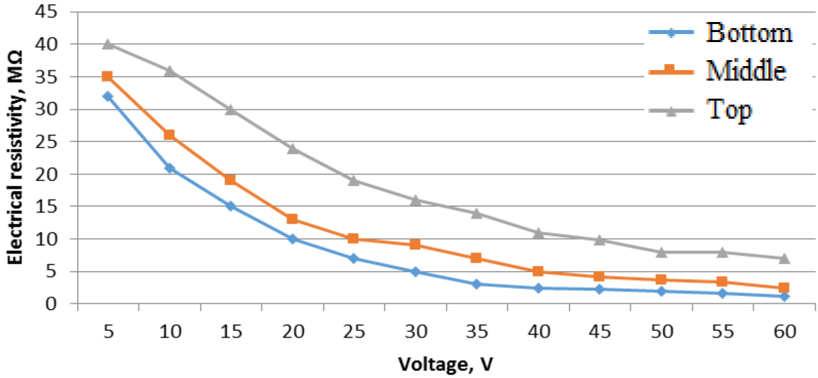


Figure. 3.6. Dependence of the electrical resistance on the supply voltage (magnetic field) when the MRF-140CG fluid that settled in one week is measured

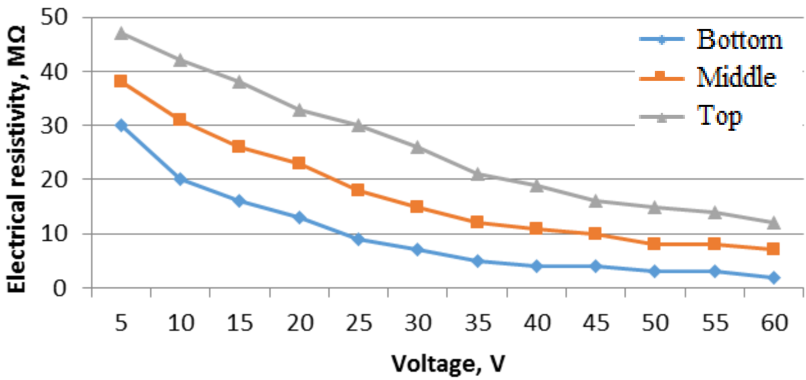


Figure. 3.7. Dependence of the electrical resistance on the supply voltage (magnetic field) when the MRF-140CG fluid that settled within two weeks is measured

As it can be seen from the obtained graphs, the resistance of the settled fluid in all three layers differs more than in the fully mixed fluid.

3.4. Determination of sedimentation in magnetoreological fluids by measuring coil magnetic induction

The MR fluid sample is placed in the glass tube, which is inside the measuring coil. The top end of the fluid sample is initially aligned with the upper side of the coil turns as shown in Figure 3.8. Because of the settling of particles, only a small amount of them are in the upper layer (level 1). There is a mudline which separates settling MR fluid in level 2 and level 1, where a lot of carrier fluid exists. On the bottom part (level 3) of the tube, there are settled particles.

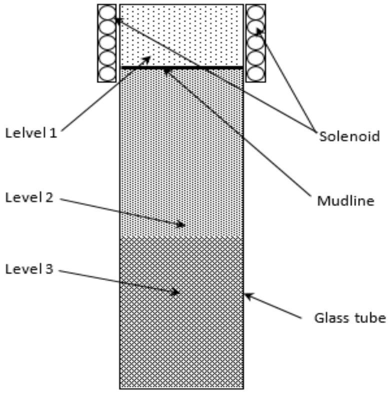


Figure. 3.8. Principal scheme: MRS in a glass flask which is disposed in a measuring coil

Using this method, the coil inductance was experimentally determined. The difference between "zero" inductance (inductor of a fully mixed fluid coil) and the inductance that was obtained during the experiment was calculated and marked with ΔL. The results are presented in Figure 3.9.

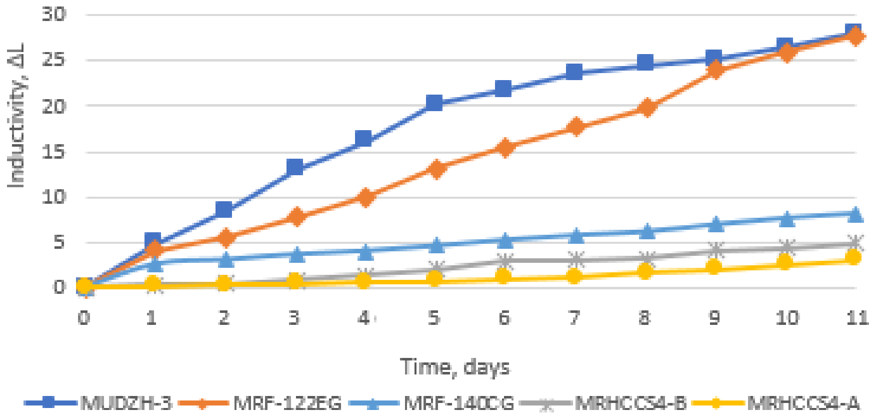


Figure. 3.9. Change in inductance of each fluid during the sedimentation

The change in the inductance of MRF-122EG and MUDZH-3 fluids is higher than that of other studied fluids. UK fluids have practically the same change in inductance, but by using this method, the sedimentation rate is slightly higher in MRHCCS4-B. Moreover, the change in fluid MRF-140CG induction is greater than that of Liquids Research co. fluids but lower than MRF-122EG and MUDZH-3.

4. CREATION OF THE DEVICE FOR THE DETERMINATION OF SEDIMENTATION IN MAGNETORHEOLOGICAL FLUIDS AND SETTING UP ITS OPERATING SPECIFICATIONS

A device for sedimentation detection and mixing inside the magnetoreological brake was developed. However, the essence is the simplicity of the electrical resistance measurement method itself, as this device can be adapted to the MR brake, clutch, etc. of different design. The device can operate completely autonomously or can be operated with the help of buttons with LED indicator lights. It has a built-in Bluetooth module, and in the future, it would be possible to control the device in this way when a gadget would be created for the smartphone.

The created device (Figure 4.1) measures the electrical resistance of magnetoreological fluids that are affected by the magnetic field. It depends on the following parameters: the temperature at which the fluid is exposed to the magnetic field, the concentration of particles, the strength of the magnetic field and the degree of sedimentation. In the absence of a magnetic field, the fluid resistance is very high (up to 600 MΩ, depending on the fluid). A simple and inexpensive sensor consisting of two contact plates, separated by a gap of no more than 1 mm, is used to measure the resistance.

The device for determining the magnetoreological fluid sedimentation is comprised of two built-in plates of electrically conductive material 2.3, separated by a gap of 1 mm. They are located in the upper and lower parts of the body, because the sedimentation of the particles at different points of the fluid results in different concentrations. The plates that mounted in the housing are insulated. Fluid 4 is leakproof by seal 5. The resistance is measured by a programmable logic controller 6.

In the upper and lower parts of the structure, the electrical resistance of the MΩ queue is measured by means of a controller and is comparable at time intervals. The degree of sedimentation is determined by their ratio. Depending on the composition of the magnetoreological fluid, the concentration of the particles and the peculiarities of the measured structure, this resistance may vary. Before using this unit, it is necessary to carry out initial measurements and calibration in order to adjust the sedimentation of a particular structure.

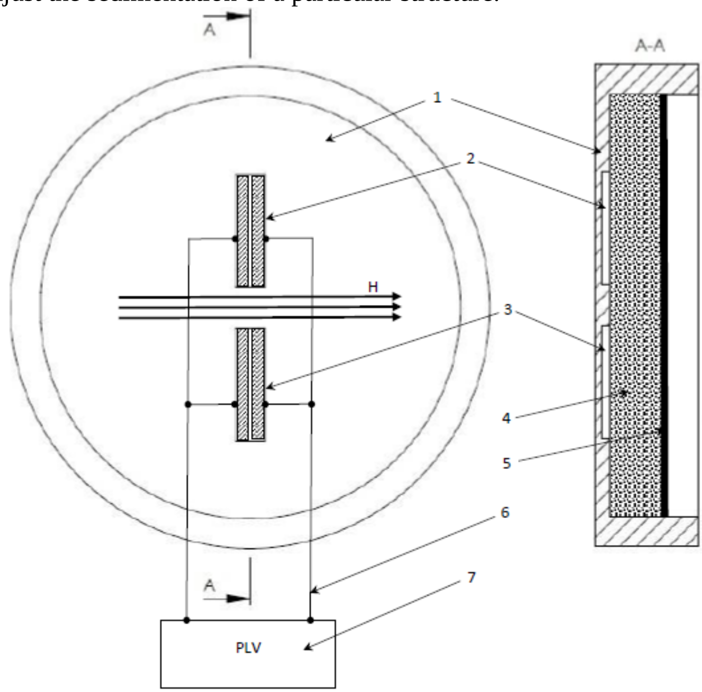


Figure. 4.1. Schematic diagram and A - A section of the device for determining the sedimentation of magnetoreological fluid: 1 – the body of the measured structure, 2 - the upper resistance measurement sensor, 3 - the lower

resistance measurement sensor, 4 - the magnetoreological fluid, 5 - the seal, 6 - the wires, 7 – the programmable logic controller.

The MR brake (Figure 4.2) [12] has been used and modified to perform the test and test the device.

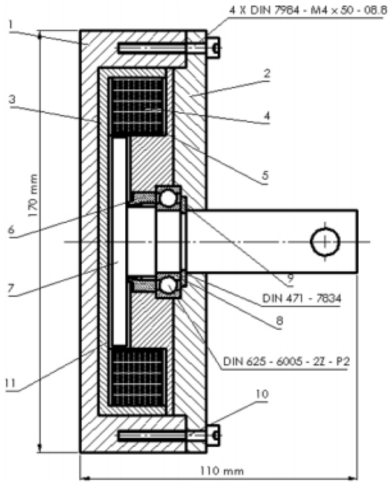
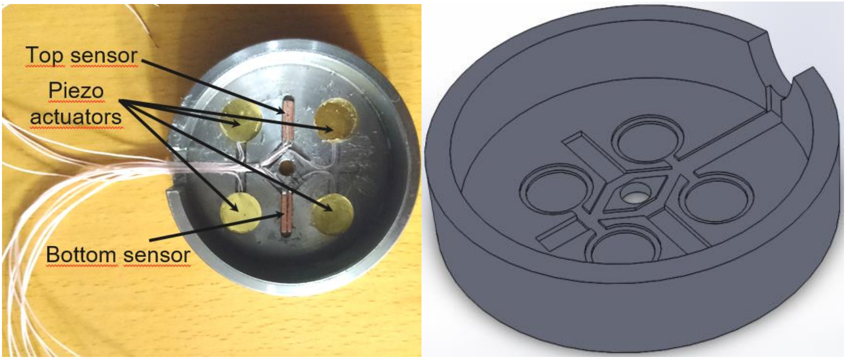


Figure 4.2. Magnetoreological brake: 1 - housing; 2 - housing cover, 3 - magnet cable, 4 - inductive coil, 5 - inductive coil frame, 6 - seal, 7 - disc, 8 - bearing, 9 - locking ring, 10 - bolts, 11 - MR fluid

The magnetorheological brake was modified to detect the sedimentation inside it and stir the fluid autonomously. For this purpose, two resistance measuring sensors were installed to determine the degree of sedimentation and four piezoelectric actuators for mixing the fluid inside. Figure 4.3, a. shows a general view of the modified part, and Figure 4.3, b. shows the part that is modelled with a computer package Solidworks.



a b

Figure. 4.3. Modified MR brake detail: a - general view, b - computer model

It has been decided to create a separate device for this modified MR brake, which can be used to determine the degree of sedimentation and properly mix the fluid inside the brake. The logical block diagram of this device is shown in Figure 4.4.

The device works as follows: the brake is connected to the device with a special connection. The relay represented by the transistor is supplied with the MR brake wheels from the step-up module at a voltage of 30V, thereby creating a magnetic field inside the brake. After 30 seconds of electrical resistance, the controller measures the resistance at the top and bottom sensors in the brake. Because of the high resistance, the devices are connected in parallel with 10 resistors and measure the change from this reference resistance. If the measured resistances are higher than the limit, the red light will illuminate with the push of a button, or if set autonomously, the 4 transistors will activate the piezoelectric relay modules that resonate the piezo-motors in the MR brake at the resonant frequency. After this procedure, the resistance is measured again, and the sedimentation mechanism can determine whether the mechanism can work or not. All the measurements and mixing data are stored on the SD card to provide the ability to view them at any time. The device itself is powered by a micro-USB connector; the recommended performance is 5V 2A.

The computer model (Figure 4.5) for device and all required components were created, and the device body was printed with a 3D printer.

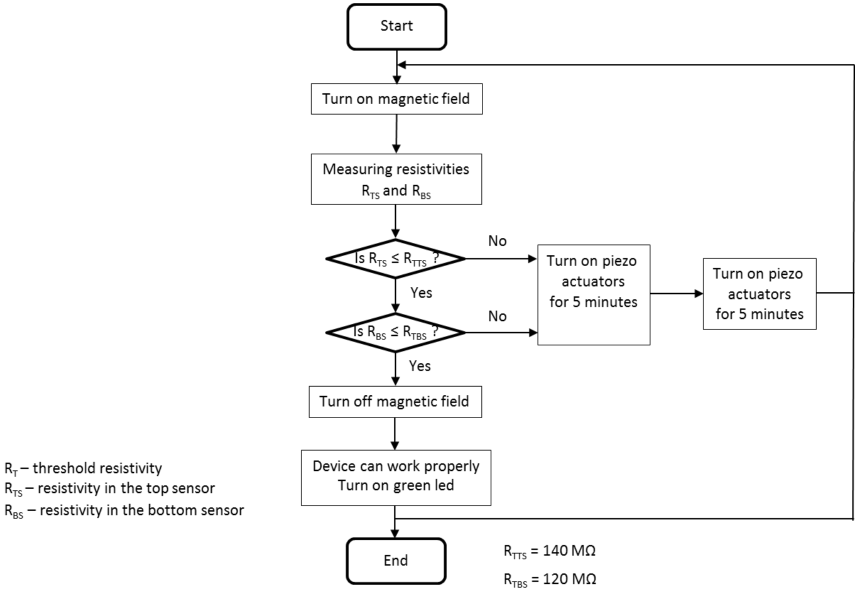


Figure 4.4. Algorithm of operation of the device that is created

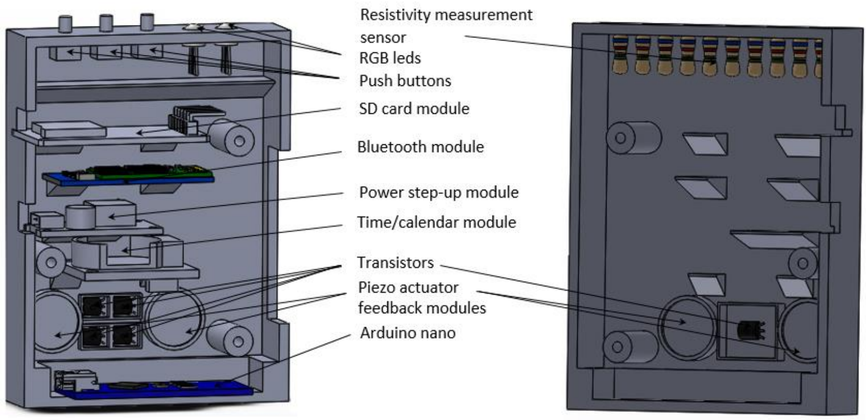


Figure. 4.5. Computer model of the created device

Inside, the device components are connected with a cable, and each has a special fitting.

GENERAL CONCLUSIONS

1. The analysis of literature and patent material in aspects of research, monitoring and maintenance of the magnetorheological fluids was performed. Familiarized with several methods for monitoring sedimentation in the MR fluids, several devices for mixing these fluids and their disadvantages were identified.
2. The particle movement in the MR fluid was mathematically described when they are in the middle of the tube or near the wall. It has been found that when the particle is closer to the tube wall, its speed is lower due to the friction forces. Moreover, a mathematical model is described where an infinite strip is affected by harmonic oscillations. The stationary and dynamic components of tangential force are described. Combining two theories, i.e., resistance to the magnetic field and determination of the degree of sedimentation, the formula of the degree of resistance to sedimentation has been derived. The theoretical and experimental results were compared. Their character is very similar, and the correlation coefficients for all five researched fluids are more than 0.95.
3. Five different fluids were tested by rheometer. The shear stress dependences of each fluid on the shear rate with and without the action of the magnetic field were obtained. When no magnetic field was applied, the highest shear stress was performed in the fluid MUDZH-3, the lowest in MRF-122EG. When 700mT magnetic field was applied to the fluids, the highest shear stress was for fluid MRHCCS4-B (68 000 Pa), the lowest for MRF-122EG (< 40 000 Pa).
4. The method to determine the level of sedimentation in MR fluids under magnetic field was created. Resistivity can be measured only when the magnetic field is applied, because otherwise, it can be very high (>600 MΩ) and cannot afford necessary information. Three special sensors to determine the electrical resistivity in the MR fluid were created. This method was verified experimentally and compared to another inductance of the coil measuring method. The correlation coefficient of these two methods for all fluids is more than 0.9, which confirms the method that was created by the author. As this method was compared with other methods worldwide, the main advantages of this method are that it is easy to adapt and it is cheaper and simpler than other similar devices.
5. The experiment of the determination of the torque moment of MR brake was carried out. Because the sedimentation of the magnetorheological fluid affects the working efficiency of the MR brake, the device to determine the sedimentation level was placed inside the brake. The sedimentation level of MR fluid inside the tested MR brake was

determined by a microcontroller by measuring the electric resistivity of the top and bottom sensors. When the level of sedimentation reaches its limit, piezo actuators turn on and mix MR fluid inside the brake.

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SCIENTIFIC ACTIVITY

Articles in journals with IF:

1. Vėžys, J.; Dragašius, E.; Volkovas, V.; Mystkowski, A.; Korobko, E. *The sedimentation of magnetoheological fluid monitoring system based on resistivity measuring*. Mechanika. Kaunas: KTU. ISSN: 1392-1207, eISSN: 2029-6983. 2016, vol. 22, iss. 5, p. 449-452.

2. Vėžys, J., Mažeika, D., Kandrotaitė-Janutienė R., Dragašius, E., Kilikevičius, A., Korobko, E.V. *Sedimentation influence on magnetorheological brake torque moment*. Strength of Materials, Vol. 50, No. 2, March, 2018. DOI: https://doi.org/10.1007/s11223-018-9979-4

3. Vėžys, J., Dragašius,E., Juzėnas,K., Korobko,E., Mystkowski,A. Comparison of different magneto-rheological fluids' stability. Journal of Measurements in Engineering. 2019.

International conferences:

1. MSM 2015, Kaunas, 2015 m. July 7-9d. J.Vėžys, E. Dragašius, V.Volkovas "Measuring of resistivity of magnetorheological fluid applied with magnetic field for determination of sedimentation"

2. "Modern technologies in mechanical engineering", Khmielnitsky nacionalinis univeristetas, Ukraina , 2016 April 21-23 d. E.Dragašius, J. Vėžys, D.Mažeika. "Experimental research of sedimentation influence for clutch with magnetorheological fluid"

3. MSM 2016, Bialystok, Lenkija, 2016 m. July 3-8 d. Joris Vėžys, Vitalijus Volkovas, Egidijus Dragašius, Darius Mažeika "Research of electric resistivity change of magnetorheological fluid under magnetic field for diagnostic of sedimentation,,

Lithuanian patent pending:

With co-authors I have applied for a Lithuanian patent: J.Vėžys, E.Dragašius, V.Volkovas, E.Uldinskas, E.Korobko. "Device to determine sedimentation in the magnetorheological fluids". Registration number: 2017 514

Information about the author

Joris Vėžys was born on April 15, 1989 in Kaunas. In 2008 he entered Kaunas University of Technology, the faculty of Mechanical engineering and Mechatronics. In 2012 he obtained a Bachelor of Sciences qualification degree in Mechatronics. In 2014 he obtained a Master of Sciences qualification degree in Mechanical Engineering. From 2014 to 2018 studies in Kaunas University of Technology Mechanical Engineering and Design Faculty, Department of Manufacturing Engineering as a doctoral student in Mechanical Engineering sciences.

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REZIUMĖ

Disertacijos struktūra ir apimtis

Daktaro disertaciją sudaro įvadas, keturi skyriai, išvados, literatūros sąrašas, mokslinių publikacijų sąrašas ir priedai. Pirmajame skyriuje pateikta aktyviųjų magnetoreologinių skysčių analizė, pjezoelektrinių medžiagų apžvalga bei kitų sedimentacijos nustatymo MR skystyje būdų apžvalga.

Antrasis skyrius – matematinis modelis. Šiame skyriuje yra matematiškai aprašytas vienos dalelės skersmens, begalinio ilgio juostos, sėdimas klampiame skystyje. Nustatyta dalelių sėdimo greičio priklausomybė nuo atstumo iki nejudamo indo, kuriame yra MR skystis. Taip pat matematiškai aprašyta harmoninių virpesių įtaka dalelių sėdimui bei susidarančios tangentinės jėgos. Šios jėgos stacionarios ir dinaminės dedamųjų pirmosios dvi aproksimacijos apskaičiuotos visiems penkiems vėliau eksperimentiškai tirtiems skysčiams. Išvesta elektrinės varžos priklausomybės nuo sedimentacijos laipsnio formulė.

Trečiasis darbo skyrius skirtas eksperimentiniams tyrimams. Jame eksperimentais patvirtinamas sukurtas matematinis modelis. Šiame skyriuje pateikiami penkių skirtingų skysčių tyrimai reometru, įmagnetinimo kreivės, nuotraukos mikroskopu, bei jutiklio elektrinei varžai matuoti kūrimo eiga. Su šiuo jutikliu atlikti sedimentacijos nustatymo eksperimentiniai tyrimai matuojant elektrinę varžą MR skystį veikiant magnetiniu lauku. Atlikti eksperimentiniai bandymai sedimentacijai nustatyti matuojant ritės induktyvumą.

Ketvirtajame skyriuje pateikti įrenginio, sedimentacijos laipsniui nustatyti bei maišymui atlikti projektavimo ir kūrimo darbai.

Kiekvieno skyriaus pabaigoje pateikti apibendrinimai. Darbo pabaigoje suformuluotos viso darbo išvados. Daktaro disertacijos apimtis 112 puslapių. Joje yra 67 paveikslai, 126 formulės ir 4 lentelės. Literatūros sąraše pateiktas 77 literatūros šaltinis.

Darbo tikslas ir uždaviniai

Šios disertacijos tikslas – sukurti įrenginį, magnetoreologinio skysčio (MR) sedimentacijos laipsniui nustatyti mechanizmuose, veikiančiuose su MR skysčiais bei skystį išmaišyti, kad palaikyti jo darbines charakteristikas.

Šiam tikslui pasiekti iškelti uždaviniai:

1. Atlikti literatūros ir patentinės medžiagos analizę magnetoreologinių skysčių tyrimo, monitoringo bei darbinės būsenos palaikymo aspektais.
2. Sukurti matematinį modelį dalelių sedimentacijai MR skystyje aprašyti, bei harmoninių virpesių įtaką sedimentacijai. Teoriškai išvesti elektrinės varžos priklausomybės nuo sedimentacijos laipsnio, veikiant skystį magnetiniu lauku ir kintant dalelių koncentracijai, išraišką R = f (S). Palyginti eksperimentiškai ir teoriškai gautus rezultatus.
3. Ištirti skirtingus MR skysčius, su reometru gauti šlyties įtempių priklausomybę nuo šlyties kitimo greičio, neveikiant magnetiniam laukui bei jam veikiant.
4. Sukurti MR skysčių sedimentacijos laipsnio nustatymo bei skysčių išmaišymo metodus, sukurti specialius elektrinės varžos matavimo, veikiant magnetiniam laukui, jutiklius bei eksperimentiškai patvirtinti šiuos metodus.
5. Sukurti įrenginį MR skysčių sedimentacijos laipsnio nustatymui bei autonominiam nusėdusio skysčio išmaišymui.

Mokslinis naujumas

- Matematiškai aprašytas magnetoreologinio skysčio dalelių nusėdimas bei nustatytos jėgos, daleles veikiant harmoniniais virpesiais.
- Sukurtas naujas sedimentacijos laipsnio nustatymo magnetoreologiniuose skysčiuose metodas, matuojant magnetiniu lauku paveikto skysčio elektrinę varžą.
- Sukurti specialūs jutikliai elektrinės varžos magnetoreologiniuose skysčiuose nustatymui.
- Pritaikyti pjezoelektriniai vykdikliai, viekiantys rezonansiniu režimu, nusėdusio magnetoreologinio skysčio išmaišymui.
- Suprojektuotas ir pagamintas originalios konstrukcijos įrenginys, galintis nustatyti sedimentacijos laipsnį magnetoreologiniame skystyje bei jį išmaišyti.

Praktinė vertė

Sukurta MR skysčių matavimo bei monitoringo daugiafunkcinė sistema skirta sedimentacijos reiškiniui nustatyti ir pašalinti. Sedimentacijos laipsniui nustatyti panaudotas naujai sukurtas skysčio elektrinės varžos matavimo metodas. Skysčio išmaišymui pritaikyti piezoelektriniai vykdikliai, kurie gaudami atgalinį ryšį nustato savo rezonansinį dažnį, o tai padeda efektyviau išmaišyti nusėdusį skystį. Sukurtu įrenginiu autonomiškai matuojamas sedimentacijos laipsnis ir gauti matavimo rezultatai įrašomi į microSD kortelę, dėlto gali būti vėliau analizuojami.

Gynimui teikiami darbo rezultatai

1. Sukurtas matematinis modelis magnetoreologinio skysčio dalelių sedimentacijai aprašyti, bei jėgos, šias daleles veikiant harmoniniais virpesiais.
2. Matematiškai gauta išraiška, leidžianti įvertinti elektrinės varžos priklausomybę, kai MR skystį veikia magnetinis laukas, nuo sedimentacijos laipsnio.
3. Reometro pagalba ištirti penki skirtingi MR skysčiai, atlikta parametrų analizė.
4. Sukurtas metodas, leidžiantis nustatyti sedimentacijos laipsnį MR skystyje – matuojant magnetiniu lauku paveikto skysčio elektrinę varžą.
5. Sukurti trys specialūs MRS elektrinės varžos matavimo jutikliai, varžos matavimui.
6. Išanalizuoti dviejų skirtingų sedimentacijos nustatymo magnetoreologiniuose skysčiuose būdus ir juos palyginti.
7. Nustatytos magnetoreologinio stabdžio stabdymo momento priklausomybės nuo magnetoreologinio skysčio sedimentacijos laipsnio.
8. Modifikuota MR stabdžio konstrukcija pritaikyta sedimentacijos laipsnio nustatymui ir skysčio, esančio viduje, išmaišymui.
9. Sukurtas ir pagamintas veikiantis įrenginys sedimentacijos laipsnio mechanizme su MR nustatymui.

Išvados

1. Atlikta MR skysčių monitoringo bei darbinės būsenos palaikymo literatūros ir patentinės medžiagos analizė. Susipažinta su keletu metodų sedimentacijai MR skysčiuose stebėti ir keletu įrenginių šiems skysčiams išmaišyti bei nustatyti jų trūkumai.

2. Matematiškai aprašytas dalelių judėjimas MR skystyje, kai jos yra indo viduryje arba prie sienelės. Nustatyta, kad kuo dalelė yra arčiau indo sienelės, tuo jos greitis yra mažesnis dėl trinties jėgų. Taip pat aprašytas matematinis modelis, kai begalinė juosta yra virpinama harmoniniais virpesiais. Aprašytos tangentinės jėgos stacionari ir dinaminė dedamosios. Apjungus dvi teorijas išvesta varžos priklausomybės nuo sedimentacijos laipsnio formulė. Palygintos teoriškai bei eksperimentiškai gautos kreivės. Jų pobūdis yra labai panašus, o koreliacijos koeficientai visiems penkiems tirtiems skysčiams yra daugiau nei 0,95.
3. Reometru ištirti penki skirtingi MR skysčiai. Gautos MR skysčių šlyties įtempių priklausomybės nuo šlyties kitimo greičio neveikiant magnetiniam laukui bei jam veikiant. Nustatyta, kad MR skysčių neveikiant magnetiniu lauku didžiausi šlyties įtempiai yra skysčio MUDZH-3, mažiausi – MRF-122EG. Nustatyta, kad MR skysčius veikiant 700 mT magnetiniu lauku ir esant dideliam šlyties kitimo greičiui, MRHCCS4-B šlyties įtempiai buvo didžiausi (68 000 Pa), o skysčio MRF-122EG šylties įtempiai buvo mažiausi (< 40 000 Pa).
4. Sukurtas metodas, leidžiantis nustatyti sedimentacijos laipsnį MR skystyje – matuojant magnetiniu lauku paveikto skysčio elektrinę varžą. Varža gali būti pamatuota veikiant skystį magnetiniu lauku, kadangi priešingu atveju ji yra labai didelė (>600 MΩ) ir nesuteikia reikiamos informacijos. Sukurti trys specialūs MR skysčių elektrinės varžos matavimo jutikliai varžai matuoti. Metodas patikrintas eksperimentiškai ir palygintas su kitu, ritės, kurios viduje yra tiriamasis MR skystis, induktyvumo matavimo metodu. Gautas šių metodų koreliacijos koeficientas visiems tirtiems MR skysčiams artimas vienetui, t.y. patvirtina darbe sukurtą metodą. Lyginant šiame darbe sukurtą metodą su analogais pasaulyje, galima teigti, jog jis yra lengvai pritaikomas, pigesnis bei paprastesnis, o tikslumas praktiškai toks pats.
5. Eksperimentiškai buvo nustatyta sedimentacijos įtaka magnetoreologinio stabdžio stabdymo momentui. Kadangi nustatyta, kad vykstant sedimentacijai MR stabdžio stabdymo momentas prastėja, nuspręsta sukurtą sedimentacijos laipsnio nustatymo įrenginį įmontuoti būtent šiame mechanizme. Įrenginys pritaikytas sedimentacijos laipsnio MR stabdyje nustatymui. Pagal MR stabdžio viduje patalpintų viršutinio ir apatinio varžų matavimo jutiklių signalus, valdikliu galima nustatyti sedimentacijos laipsnį. Esant sedimentacijos laipsniui didesniam už užsiduotą normą, pritaikyti pjezoelektriniai vykdikliai leidžia atstatyti MR skysčio darbines charakteristikas.

UDK 681.521.7+665.767+681.586.773](043.3)

SL344. 2019-04-23, 2,5 leidyb. apsk. l. Tiražas 50 egz.
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