KAUNAS UNIVERSITY OF TECHNOLOGY
ALEKSANDRAS STULGINSKIS UNIVERSITY

VIKTORIJA MAČIUKIENĖ

DEVELOPMENT AND RESEARCH OF DEVICE FOR MAGNETORHEOLOGICAL FLUIDS PARAMETERS SETTING

Summary of Doctoral Dissertation
Technological Sciences, Mechanical Engineering (09T)

2016, Kaunas

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KAUNO TECHNOLOGIJOS UNIVERSITETAS
ALEKSANDRO STULGINSKIO UNIVERSITETAS

VIKTORIJA MAČIUKIENĖ

ĮRENGINIO, SKIRTO MAGNETOREOLOGINIŲ SKYSČIŲ PARAMETRŲ NUSTATYMUI, SUKŪRIMAS IR TYRIMAS

Daktaro disertacijos santrauka
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INTRODUCTION

Relevance of the topic

Magnetorheological and electrorheological fluids (MRS and ERS) belong to the group of active fluids that are increasingly used in different mechatronic devices. Using these smart and active fluids, the energy consumption and weight of construction can be reduced, conversely velocities and validity are increased. Such kinds of mechanisms are used in serious areas related with safety: automotive suspension parts, shock limiter, etc. These fluids are very perspective and innovative materials. For this reason and to ensure that systems with MRF and ERS operate reliably, rheological fluids stability systems were created. There are many constructions where rheological fluids are confined and mechanical mixing of the fluids are impossible. Therefore it is necessary to use a different type of rheological fluid stability system, i.e. installing a monitoring system locally in the device. Emphasizing the fact that magnetorheological fluids depend on the non–Newtonian fluid group, viscoelastic fluids subgroup. It can be said that monitoring these fluids and diagnosis is much more complex and expensive than the Newtonian fluid. The main rheological fluids properties testing device is rheometer (expensive and stationary device). This predicament of measuring conditions raised the main aim of the research – to create cheap, mobile and locally measuring magnetorheological fluid characteristic devices. In this century of modern technologies, developing very rapidly precision devices requires the following requirements: small construction size, speed, reliable operation, working conditions unevenness, a wide range of operating speeds. Taking these requirements into account, the decision that piezoelectric actuators are a perfect implement. Well known piezoelectric material advantages consist of: operating efficiently over a wide temperature range, insensitive to magnetic fields (this is one of the main positive indicators during the experiments), high power at low speeds and many other positive characteristics. Combining the piezoelectric actuator positive qualities and challenges raised by research, several magnetorheological fluid monitoring and diagnostic systems or methods have been developed.

The aim and objectives

The aim of the dissertation – create reliable, mobile revise device, capable of being locally set for magnetorheological fluid rheological properties.

Tasks solved in order to realize the purpose:

1. Perform literature and patent analysis in magnetorheological fluid investigation, monitoring and applicability aspects.

2. Design specially shaped electromagnet, which effectively changes the viscosity of a magnetorheological fluid from the initial B = 0 T to the maximum achievable magnetic induction B ~ 1T limit.
3. Based on the finite element method, investigate the dynamic characteristics of the piezoelectric actuator.
4. Create and experimentally investigate the magnetorheological fluid rheological parameters setting device.
5. Create a parametric test device for the magnetorheological fluid stability measurements, using electromagnetic coils and piezoelectric transducers.

Research methods

The thesis was carried out by means of theoretical, analytical and experimental research. Theoretical studies was made using the finite element analysis COMSOL Multiphysics 4.4 computer software package. With this software package, the electromagnet magnetic field distribution in a magnetic conductor and bending deformation type piezoelectric actuator working were calculated. Considering to mathematical numerical simulation results, the most relevant parameters of the bending -type piezoelectric actuator, which is used in the system of rheological parameters detecting system, were selected. After checking the magnetic field distribution in the magnetic conductor, and most importantly in the air gap, the results were positive enough for successful experimental studies. The experiments of active fluids were performed in the Institute of Mechatronics.

Scientific novelty

- Created two rheological fluids homogeneity supporting methods: electromagnetic and ultrasound
- One of the created homogeneity supporting methods is multifunctional: not only for stability supporting also for fluid continuous monitoring
- Piezoelectric materials used for magnetorheological fluid dynamic viscosity measurements
- Designed and produced a new electromagnet construction, whose corresponding requirements, in an air gap between magnet poles, develops magnetic induction B equal 1T.
- Created original construction piezoelectric actuator – sensor (two in one), whose contact element operates in shear mode.

Practical value

Created two active fluids rheological parameters measuring and monitoring systems. One of them multifunctional – for sedimentation phenomena detection and removal. The other one, the main part of this dissertation – a magnetorheological fluid dynamic viscosity measuring system. Using such kind of devices is enough for the exact measurement of magnetorheological fluid rheological properties. The economic aspects of these measurement devices is highly acclaimed, because the practice value is very high and price is very low. Supporting comparison rheometer, whose price is relatively very high compared with the developed system.

The work results for the dissertation defense

1. Piezoelectric diagnostic system for magnetorheological fluid long-term stability and working characteristic experiments.
2. Magnetic field distribution in a magnetic conductor experiment results.
3. The piezoelectric actuator selection results.
4. Created magnetorheological fluid measurement system methodology.

Thesis approval

Research results were presented in 3 Institute for Scientific Information databases „ISI Web of Science publications with a citation index. Also, in 3 Institute for Scientific Information databases „ISI Web of Science publications, citation -free index. In addition, 11 other peer-reviewed scientific journals published articles and the resulting scientific invention patent of the Republic of Lithuania.

Dissertation structure and volume

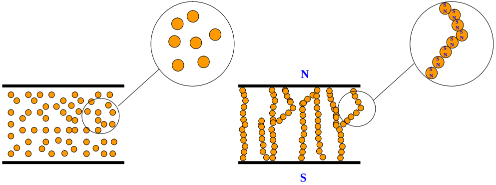
The Doctoral dissertation consists of an introduction, four chapters, conclusions, references, scientific publications and annexes. The first section reviews the active rheological fluid analysis to examine their operation modes. A detailed analysis of viscosity measurement devices and discusses in detail the piezoelectric materials and piezoelectric actuators. Chapter two - research methodology. This section is the numerical simulation. Mathematical modeling consist of two parts: electromagnet and piezoelectric actuator research using COMSOL software. The third chapter of the work – experiment of the magnetorheological fluid viscosity measurements. The fourth chapter presents the piezoelectric diagnostic systems and the rheological fluids long-term stability experimental studies. At the end of each part a chart is submitted with summaries. At the end of the total dissertation – conclusions. Dissertation volume is 118 pages. There are 115 figures, 73 formulas and 6 tables. Literature list includes 88 references.

Used words phrases:
MRS – magnetorheological fluids.
ERS – electroreological fluids.
MR – magnetorheological.
LDE – Life time dissipated.

1. ANALYSIS OF LITERATURE AND TASKS FORMULATING

1.1. Active rheological fluids

Magnetorheological and electrorheological fluids – it‘s smart materials are capable of changing behavior from liquid to solid after exposure to external simulation – respectively magnetic and electric fields. In this dissertation, the research tool is magnetorheological fluid. The main components of the MR fluid is magnetizable micro particles and some carrier fluid. This is an easy flowing liquid. When the magnetic field is added, iron particles take on a magnetic dipole moment, which is equal with the external field. Then, in parallel to the field (Fig. 1.1 right) particles are located in a straight chain.

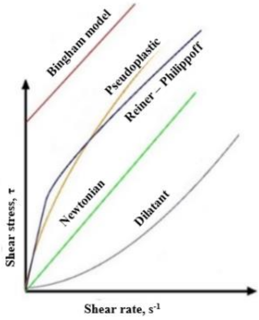


1.1 fig. MRS functioning scheme: a-no magnetic field; b-particles distribution in magnetic field.

Conversely, when the fluid is flowing the iron particles are not flowing together and thus stops the MRS flow. The viscosity of the magnetorheological fluid when the magnetic field is “on” changes in a few seconds. The examination of a typical MR fluid composition can be argued that they are composed of 20-40% plastic and relatively pure iron particles. An example could be the iron particles, which are displayed in mineral or synthetic lubrication, glycol or water. Suspended particles (in a fluid) magnetic saturation level leads to determine the MR fluids viscosity. In practice, preferred particles can be used which are pure iron particles. Their magnetic saturation equal 2, 15 T. Mostly, MR fluids magnetizable particles have a diameter of 3 to 5 µm. Also a very important factor is the temperature fluctuation because viscosity inversely to increasing temperature i.e. increasing the temperature decreases the viscosity and also decreases stress, but this phenomena is more typical for electrorheological fluids than for magnetorheological fluids

1.2.Non – Newtonian fluids and numerical modeling

Generally, fluids are divided into Newtonian fluids and non – Newtonian. The most obvious example of Newtonian fluid is water. Its shear stress dependence on shear rate is linear, whereas with non – Newtonian fluids, when shear stress dependence on shear rate, is non – linear and dependent on time t. A good example of this is the definition of variable viscosity engine oil, whose viscosity changes are linear fixed to temperature changes. However, for some non – Newtonian fluid the Newton laws are not valid. Even in such conditions, when both the pressure and the temperature are constant and viscosity is variability. Such kinds of fluids viscosity is dependent on the flow duration and velocity gradient. Visually it can be seen in figure 1.2. in the Bingham model that from the rest of the other fluids (Newtonian, pseudoplastic and etc.) are different in that they have the primary shear stress $\tau>0$.



1.2 fig. Newtonian fluid and non – Newtonian fluid comparison

Bingham fluids do not start to flow until the stress value does not exceed the yield strength of stress. In general, the definition rheology is – fluid flow deformation response to fluid stress. To force incompressible fluids requirement – defeat shear stress. During the fluid flow examination, the sample is placed between two parallel plates with surface area A. where the top plate moving speed is V, which is activated by force F, while the bottom plate is stable and immobile.

In these conditions, the following definitions:

Shear stress $\boldsymbol{\tau}$ – It is defined as the force to area unit:

$$\tau = \frac{F}{A} \tag{1.1}$$

Shear rate $\dot{\boldsymbol{\gamma}}$ – If the speed V is constant, then the shear rate $\dot{\gamma}$ is the speed difference between the two plates divided by the gap height h.

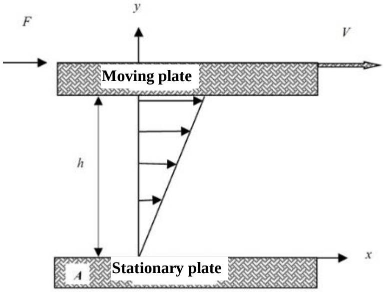
Viscosity – Newtonian fluid viscosity defined by Newton's laws and the viscosity of expression follows:

$$\tau = \eta\dot{\gamma} \tag{1.2}$$

The fluid viscosity η defines a fluid shear force resistance, which is called dynamic viscosity. Kinematic viscosity expression follows:

$$\upsilon = \frac{\eta}{\rho} \tag{1.3}$$

Here ρ – material density kg/m^3



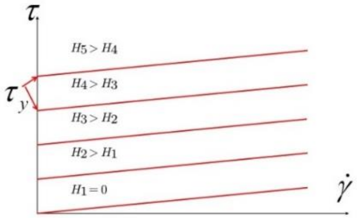
1.3 fig. Shear phenomena in fluid between two parallel plates

Magnetorheological fluids rheological characteristics directly depends on the surrounding magnetic field. The Bingham model is a base model, which describes the magnetorheological fluids behavior. With this model, the shear stress change Δτ is linearly dependent on the shear rate $\Delta\dot{\gamma}$ change. The point where the shear rate is $\dot{\gamma}$=0 is called the yield point or stress thresholdτ_y.

Yield stress$\tau_y$directly depends on the magnetic field H.

$$\begin{cases} \tau = \tau_y + \eta\dot{\gamma} & \tau \geq \tau_y \\ \dot{\gamma} = 0 & \tau < \tau_y \end{cases} \tag{1.4}$$

However, this model does not provide any information, when the magnetorheological fluid behavior is in „before flow„ fluid behavior. In this state the does not valid dependences shear stress τ on shear rate$\dot{\gamma}$ (when$\tau < \tau_y$) is not valid. This „before flow“mode can be investigated by using microscopic examination and monitoring status.

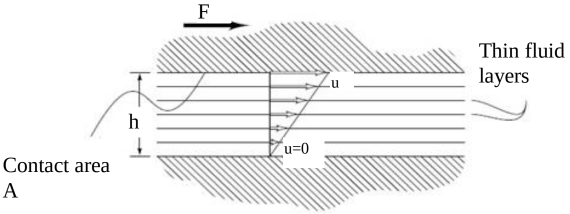


1.4 fig. Bingham model

Research magnetorheological fluids are related to the non – Newtonian fluid group, viscoplastic subgroup. Prior to the critical shear stress, fluids are not set in deformation, it is like a solid body. When the shear stress value is at maximum, the fluids start to flow. Fluids of the Bingham model is a special viscoplastic fluids type, which expresses the direct dependence of the shear stress on shear rate of shear change, at the moment the fluid begins to flow. Good example is a toothpaste tube, the toothpaste does not flow until the tube is pressed.

1.3. Analysis of viscosity measurements devices

The fluid viscosity - resistance to shear and tensile deformation – measured viscometer or rheometer. Rheometer used for cases when the fluid viscosity cannot be determined by one viscosity value and the fluid is characterized by viscosity dependence on an external parameter. Viscosity - is a quantitative measure. Fluid resistance for flow process. Viscosity is dynamic (or absolute) and kinematic. Dynamic viscosity η – dynamic viscosity coefficient or dynamic viscosity, characterized by fluid (gas) and their numerical value equal to the internal friction force F, when contact of area equal to 1 m^2 , and the speed gradient module equal 1s-1. The minus sign indicates that the force in the opposite direction to the direction of fluid flow.



1.5 fig. Graphic view of dynamic viscosity

$$\eta = \frac{F}{A\left(\frac{u}{h}\right)} = \frac{\tau h}{u} \qquad (1.42)$$

Kinematic viscosity is defined as the ratio of the dynamic viscosity of the fluid density.

$$\upsilon = \frac{\eta}{\rho} \qquad (1.43)$$

Although viscosity can be perceived as the resistance to the flow. When the material viscosity is major, the resistance is major too. Therefore, viscosity measurement is very important in engineering.

There are several basic types of viscometer used in the laboratory or portable testers:

U – Shaped tube viscometers. These viscometers measure dynamic viscosity. The measuring principle is very simple: monitoring how long it takes the process in the U shape capillary tube between two points.

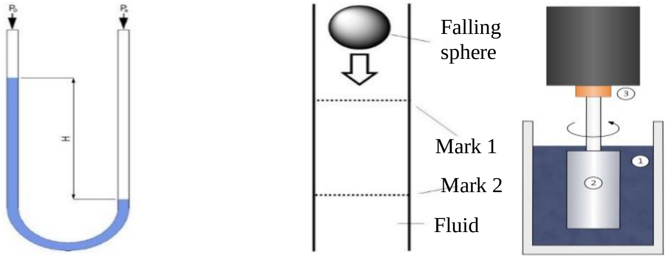
Falling sphere viscometer. These viscometers use a falling spherical ball for the viscosity measurements. Measuring the falling time between two points:

$$F = 6\pi\eta rv \tag{1.44}$$

Hereη–dynamic viscosity, v –ball speed, r –ball radius.

Rotation viscometers. These viscometers measure the resistance of torque. There are a few of this type viscometer.

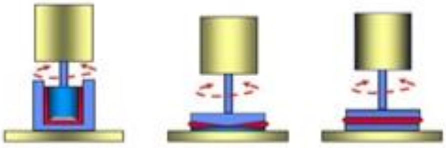
Bubble viscometers. These instruments measure the time in which the bubbles rise to the surface of the fluid.



a) b) c)

1.6 fig. Several types of viscometer: a) U-shaped tube; b) falling sphere; c) rotation viscometer, wherein 1 – fluid, 2 – measuring tool, called as spindle, 3 – torque measuring device.

Rheometer. The following measurement devices are for non – Newtonian fluids measurements. Usually such class of fluids are influenced by environmental factors.



a) b) c)

1.7 fig. Rheometer with different plate geometry

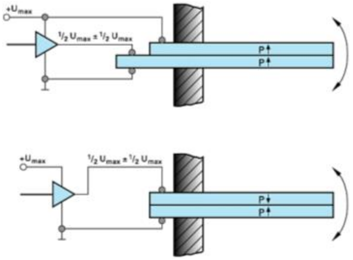
The dissertation's research main object is magnetorheological fluids. These fluids is non – Newtonian fluids. Their viscosity can be measured with a rheometer Rheometer operates on the principle that the liquid is placed between two plates fig.1.7, where the plate geometry is different depending on the viscosity of the fluid. As seen in figure (a) – rheometer, plate geometry is concentric cylinders. This type of rheometer measures the fluids with a viscosity from very low viscosity to medium. Geometry, when the upper plate is a rotating cone, stationary - plate (b) – the rheometer designed to measure from very low viscosity to highly viscous liquids. In figure (c) there are two parallel plates, bottom – stationary, the upper rotating. This type of rheometer, the liquid and the viscosity is from liquids to solids. Rheometer measures the flow of the fluid flow. Specifically - forces (as shear) directly related to fluid flow physics. In the rheometer, the measured outgoing value is expressed as a power (pressure) changing in the flow material. Generally, there are two types of rheometer: rotation or shear rheometer and extensional rheometer. During research, the rotational rheometer will be examined in detail. For magnetorheological fluids, measurements using the rotational rheometer with two parallel plates "head" between is placed in a magnetic fluid.

1.4. Classification of piezoelectric actuators

Piezoelectric effect is very applicable. Examples: speakers and calls, gas burners. Piezoelectric ceramics using mechanical effects such as pressure, the acceleration can convert them into electrical energy or vice versa - electrical energy into mechanical. The Piezoelectric ceramic used in a variety of converters can also work in different frequency ranges. Piezoelectric elements used in actuators can be various forms. They are solid materials with unlimited resolution, which is currently the most dependent on the piezoelectric actuators controlling the electronic hardware options. The main idea of the dissertation aim – magnetorheological fluid viscosity measurement using piezoelectric materials.

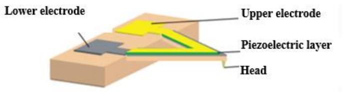
Bending deformation piezoelectric actuators

Piezoelectric bending deformation actuator movement obtained on the piezoelectric layer elongation. Such kind of actuators consist of two or more layers (at least one must be a piezoelectric ceramic layer), they polarized such that the adjacent layers go in opposite directions. Opposite piezoelectric layers prolongations creates an internal bending moment similar to bending sticks.



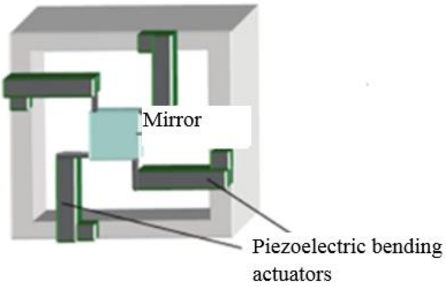
1.8 fig. Piezoelectric bending deformation actuator, which uses two piezoelectric ceramic layers parallel and series connection, schemes

Piezoelectric bending deformation actuators are widely used in scanning devices (1.9fig.). When piezoelectric actuators used in scanners increase scanning speed, because the actuator resonant frequencies are high.



1.9 fig. Bending deformation piezoelectric actuators used in the atomic microscope structure

Another bending deformation actuator example is in 1.10fig, showing a mirror control system. Devices that use piezoelectric bending deformation actuators have speed and accuracy. In many of these devices, mirrors can make one or two-way movements.

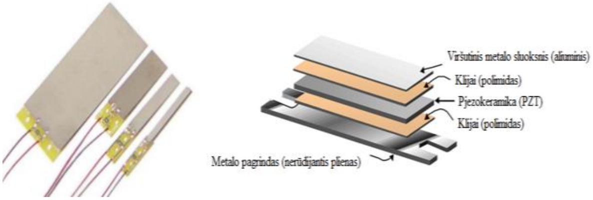


1.10 fig. Piezoelectric bending deformation actuator for mirror control in a scan system

There are a few types of bending deformation actuators: unimorphs (with one piezoceramic layer), bimorphs (with two piezoceramic layers) and multilayers.

1.11 fig. Multilayer PICMA company bending piezoelectric actuator

The USA Company „Piezo Systems“ offers bending piezoelectric actuators (1.12 pic.), which are easily consolidated and the electronic circuit, which has a resistance to protect the consumer from the piezoelectric actuator discharge. These actuators can achieve the shift to 1, 26mm. According to their shape bending, actuators can be thin stick, tube, disk, and so on. The USA Company „Face International Corp“manufacture Thunder type, special technology actuators (1.12 pic.). The Arc – shaped bending actuators having good amplitude characteristics.



a) b)

1.12 fig. Piezo Systems bending deformation actuators: a) multilayer b) „Thunder“ type piezoelectric actuator

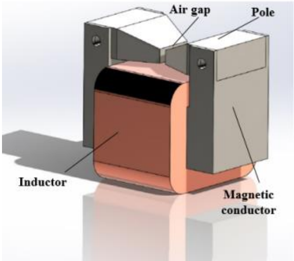
After the piezoelectric actuators analysis – chosen bending deformation actuator for following researches was selected, which will be examined analytically and experimentally.

2. NUMERICAL SIMULATION OF MAGNETORHEOLOGICAL FLUID RHEOLOGICAL PARAMETERS SETTING DEVICE

2.1. Electromagnet numerical modeling, design and analysis for magnetorheological fluid viscosity control

In picture 2.1 is a three-dimensional view of an electromagnetic coil, which is an accurate and reliable electromagnetic coil designed by SolidWorks 3D engineering solutions package. Significant electromagnetic coil magnetic specifications are; length Lm=280 mm, significant cross-sectional area (air gap) Sm=100 mm^2. The number of coil windings N=725. The magnetic circuit is characterized by a magnetic permeability µ. Magnetic permeability describes the material properties, its ability to strengthen the magnetic field, piercing the same material. During the research, magnetic conductor made of steel AISI 1018 was selected. Steel permeability is obtained by solving the basic magnetic equations. There are two important phenomenon: the magnetic field in the air gap (3 mm in width) and the value of the magnetic field, when magnetorheological fluid is filled in the gap. As well-known magnetorheological fluid magnetic properties – non – linear The geometry of the magnetic circuit at the air space has therefore been made more complex. Reduced area S, for the reason to concentrate magnetic field lines and increase magnetic induction B value, it express formula 2.8:

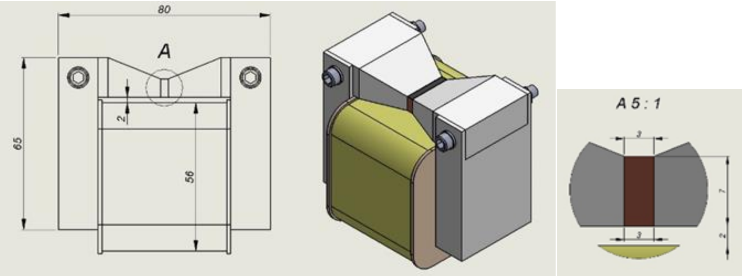
$$B=\Phi/S \qquad (2.8)$$



2.1 fig. A three-dimensional image of electromagnetic coils

2.2.Numerical modeling of magnetic fields

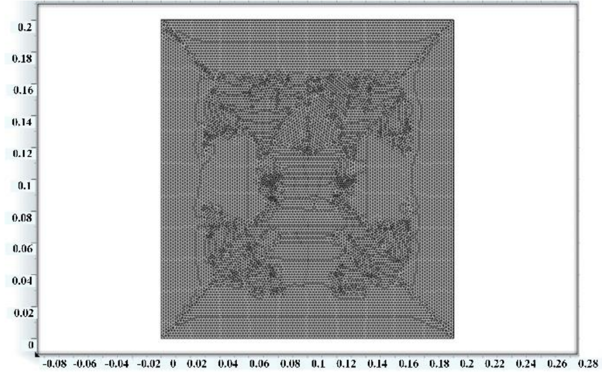
The magnetic fields of numerical simulation begins with a test item – detailed view of an electromagnet and geometrical parameters, are depicted in figure1.14.



a) b) c)

2.2 fig. Electromagnet a) geometric model; b) 3D model; c) detailed air gap view

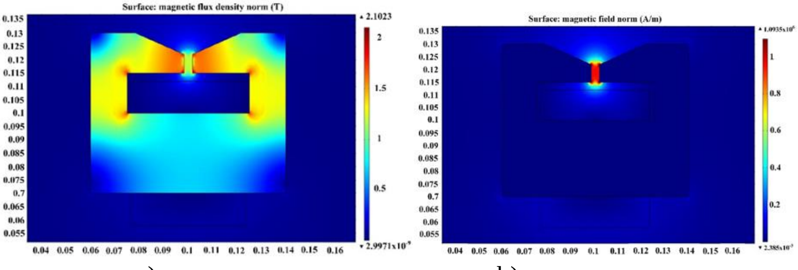
Simulation performed with Comsol Multiphysics software version 4.3. The magnetic circuit is closed and the cross-sectional area S is a stable value, the magnetic flux Φ is concentrated in a magnetic pole. Magnetic flux value in the air gap and in the magnetorheological fluid is equal $\Phi_{mr} = \Phi_{oro}$.



2.3 fig. Finite elements of electromagnet

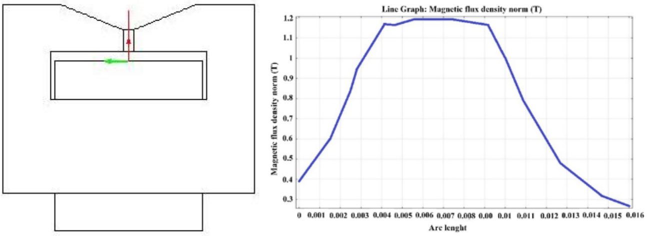
Below is a geometric model of the test object, including a description of the geometric object, parts tags and finite element mesh. The latter is designed to visualize the simulation accuracy. As mentioned before, the main magnetic quantity is magnetic induction B (T).

Calculation, when the current in a coil is 3A.



a) b)

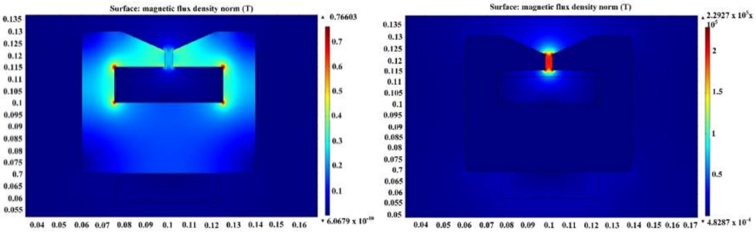
2.4 fig. The magnetic flux density distribution, when the current in a coil is I= 3A



a) b)

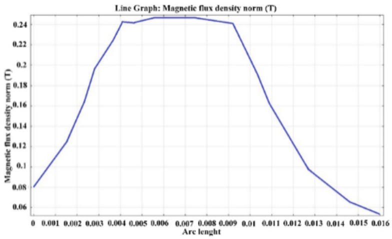
2.5 fig. a) Field line, showing the magnetic flux density value; b) magnetic flux density in field line

Calculation, when the current in a coil is 1A.



a) b)

2.6 fig. The magnetic flux density distribution, when the current in a coil is I= 3A



2.7 fig. magnetic flux density in field line

After numerical, magnetic field's distribution in electromagnet, modeling the result is very close to the experimental calculations. Magnetic induction B (T) in air gap, when the current I=3A equal 1.17T.

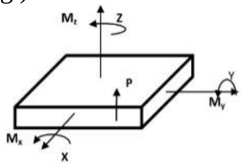
Intermediate calculation results (Comsol Multiphysics 4.3 software) are presented in a table 2.1. In the following sections of the dissertation is the studied piezoelectric actuator.

2.1 table. Magnetic induction size obtained by numerical simulation

Current in a electromagnet I (A)	Magneticfield induction B (T)
0,5	0,13
1	0,26
1,5	0,47
2	0,77
2,5	0,97
3	1,17

2.3. Piezoelectric actuator numerical calculation

Piezoceramic materials – nonlinear solid solutions. It has strict orientation domains i.e. the residual polarization. Piezoceramics structurally defined as heterogeneous polycrystalline system. Roasting material obtained dielectric structure – segnetoelectric ceramic - does not have piezoelectric properties as long as it is not non polarization. Piezoceramics, like any other dielectric material has dipole cluster areas - domains. Placed ceramic material in an electric field, the domains abrupt reorientation happens. Total polarization occurs in piezoceramics element, which does not disappear and in non – electrical field. Piezoceramics already has a well-defined structure and set coordinate axes, therefore, the polarization vector direction is one of the most important characteristics of multidimensional piezotransducers. Piezoelectric elements axes orientation is set so that the Z-axis (piezoaxis) direction coincides with one of the polar axes, other two axis X (optical) and Y (mechanical) where selected according to the right-handed coordinate system (2.9fig.).

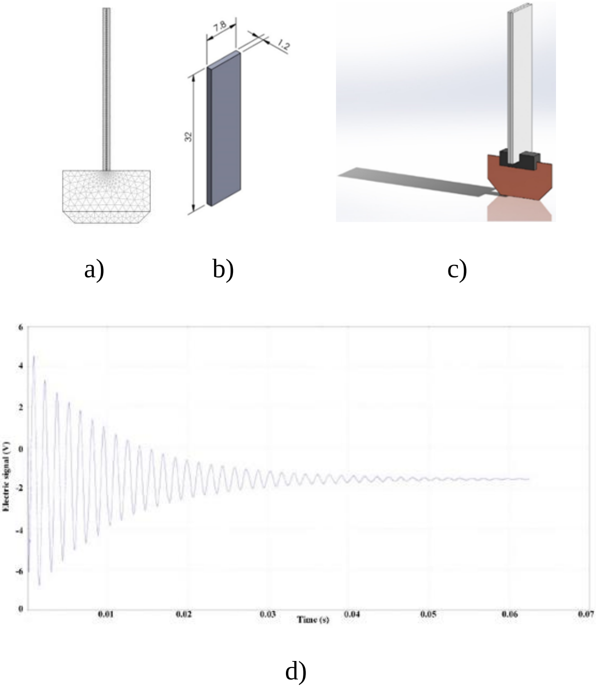


2.8 fig. Piezoelectric elements orientation of the axes

In order to create a dynamic parameter shift in a viscous environment i.e. making viscosity measurements in magnetorheological fluid, cantilever type piezoelectric actuator was chosen. This actuator affects both direct and inverse piezo effect. The Piezo-electric actuator consists of three layers: two piezoelectric layers and one epoxy adhesive that connects them. When the actuator is in active mode, one of the layers is tension and the other one compressed.

The Piezoelectric actuator, which has been simulated, is made of two ceramic layers with a thickness of 60 µm. This is the standard in order to achieve amplitude crunches together with a small force voltage. Maximum crunches is +/– 345 µm. Blocking force is 2,25N. Piezoelectric actuator consist of three layers fig. 2.10: two of them placed at the bottom and top connected by piezoelements electrodes, third in between – epoxy glue.

<u>Static task.</u> Comsol Multiphysics modeling package calculation results:



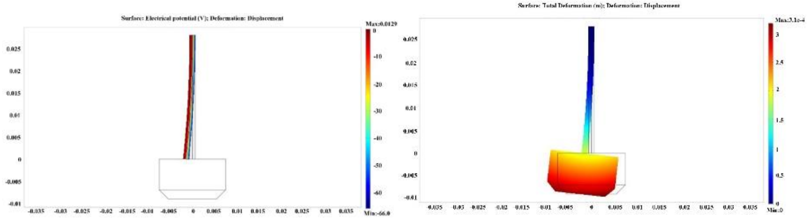
a) b) c)

d)

2.9 fig. a) piezoelectric actuator with KE finite element mesh; b)Piezoelectric actuators geometry c) piezoelectric actuator 3 – D view d) Piezoelectric actuator shock transition process characterization

2.9 fig. a) – this is a geometric model of the research object, including a description of the object – geometric, parts tags and finite element mesh. The latter is designed to visualize the simulation accuracy. Figure 2.10 (d) shows a shock transition process characterization performed when the damping of c = 0. This is the view of how quickly the vibrations of the actuator is damped with starting pulse voltage Uj=66V. Damping takes place in the air, the piezoelectric actuator oscillations decreases in the air due to the internal decay rate of the internal friction of the material:

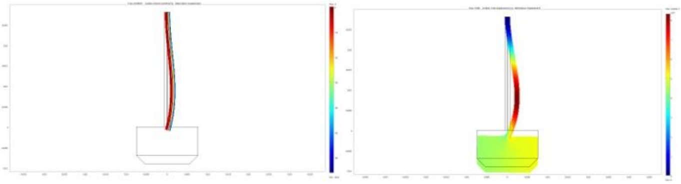
$$C_{sum} = C_{environment} + C_{piezo};\ C_{air} \ll C_{piezo} \qquad (2.25)$$



a) b)

2.10 fig. a) voltage field distribution in both piezoelectric actuator layers ; b) displacement field distribution across the length of the piezoelectric actuator including a contact element

Figure 2.11 (a) shows the voltage distribution in the active and passive piezoelectric actuator layers. Force voltage Uj=66 V supplied to the active piezoelectric layer where the current constant and viscosity C = to 0. Figure. 2.11 (b) shows piezoelectric actuator bending value at different points. Maximum bending values are at contact element points. Minimum bending values are around the fixation zone. Further, solving the same static task by replacing one condition and passing from damping C=0 to other boundary condition C>>0 (2.12 fig.)



a) b)

2.11 fig. a)voltage field distribution in both piezoelectric actuator layers b) displacement field distribution across the length of the piezoelectric actuator including a contact element

Fig. 2.12 (a) Shows the voltage field distribution in active and passive piezoelectric actuator layers. Force voltage Uj=66V. Uj supplying to active layer, when current is DC and environmental viscosity C>>0.

Quasistatic task. The piezoelectric actuator operates in low frequency range f=10Hz. Therefore, the dynamic task of reducing and solving the quasistatic task uses the following parameters:force voltage U_j=66 V, piezoactuator vibration frequency f=10 Hz, damping C=0 Ina voltage dependency from the time curve (fig. 2.13 a) where the green curve = force voltage of the active piezoactuator layer, and the blue curve = voltage of sensor signal U_s.

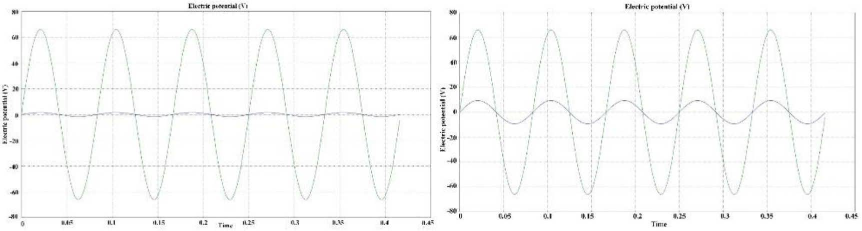
Ratio of voltages:

$$\frac{U_j}{U_s} = \frac{66}{3} = 22$$

Force voltage Uj=66 V, piezoactuator vibration frequency f=10 Hz, damping C>>0. In a voltage dependency from the time curve (fig. 2.13 b) where the green curve = force voltage of active piezoactuator layer, and the blue curve = voltage of sensor signal Us.

Ratio of voltages

$$\frac{U_j}{U_s} = \frac{66}{10} = 6.6$$



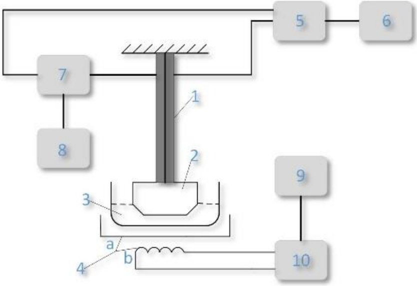
a) b)

2.12 fig. a)Voltage dependency from time in both piezoelectric actuator layers (C=0);b) Voltage dependency from time in both piezoelectric actuator layers (C>>0)

To determine the magnetorheological fluid viscosity, designed and numerically investigated electromagnet was selected, in addition to the numerically evaluated suitable geometry and bending deformation modes actuator. The electromagnet geometrical parameters allows in a 0.5 ml container volume of magnetic induction density a range from 0 to 1.2 T. In the following stage, experimental research will be carried out based on the modeling results.

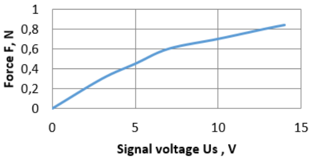
3. EXPERIMENTAL INVESTIGATION OF MAGNETORHEOLOGICAL FLUID RHEOLOGICAL PROPERTIES

Fluids rheological properties investigation – a material deformation and yield survey. Magnetorheological fluid is structurally a complex test substance. In this dissertation is proposed a new test system, which is characterized by low price and compact composition, along with the ability for measurements to be taken locally. Research of a magnetorheological fluid volume of 0.5 ml, which is poured into a copper 3.5mm width of container.

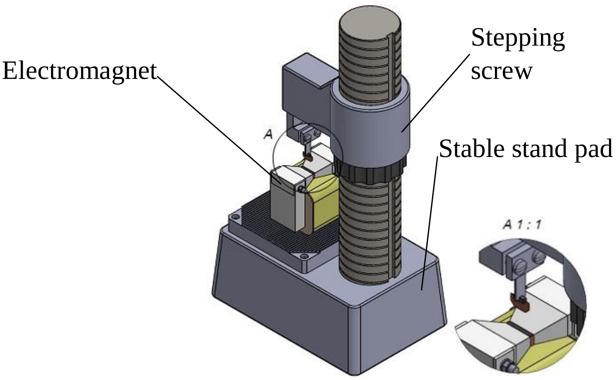


3.1 fig. Structure scheme of experimental stand. Experimental stand consist of: 1 – cantilever piezoelectric actuator CMB05 (Noliac A/S); 2 – cooper plate; 3 – vessel of magnetorheological fluid; 4 – electromagnet a-winding, b-magnetic conductor; 5 – analogical digital converter PicoScope 3424; 6 – computer; 7 – amplifierEPA104; 8 – signal generator Agilent 33220A; 9 – ammeter; 10 – power supply

Measured blocking force – the signal force of an inactive layer. It was experimentally carried out with the force measuring device MARK – 10BGI. The force measuring device sensor was connected to the investigation piezoelectric actuator passive layer and a force voltage supplied to the active layer. The result – from the active layer transmitted pressure, which the scanner generated in newtons. Experimental test has been carried in the air, when the piezoelectric actuator free end, with contacting element, has been immersed into magnetorheological fluid.



3.2 fig. Dependence signal voltage in passive layer on force

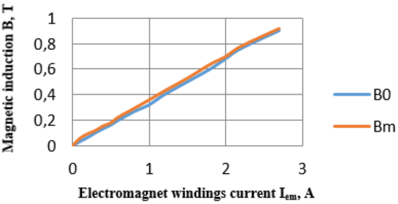


a) b)

3.3 fig. The main experimental test part,designed in SolidWorks software. a – general view of the stand with electromagnet; b – electromagnet poles, magnetorheological fluid vessel and piezoelectric actuator wit contact element view

Figure 3.3 is the central and main part of the experimental stand. The stand has two screw feeds, one with a higher step, the other a smaller step. This allows free accurate movements and exactly associate contact element surface with the magnetorheological fluid. Magnetic induction value of the electromagnet in the air gap and in the magnetorheological fluid is measured with the magnetic field density measuring device Š1-8. Experimental tests show, varying current in electromagnet windings from 0 to 3 A shows a magnetic induction results B=0.95 T. Performing a comparison of magnetic induction in various types of calculations and experiments:

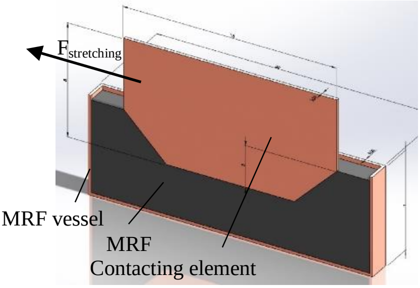
$B_{analytical} = 1\ \mathrm{T} \sim B_{calculating} = 0.942\mathrm{T} \sim B_{comsol\ modeling} = 1.15\mathrm{T} \sim B_{eksperimental} = 0.95\mathrm{T}$



3.4 fig. Magnetic induction dependence on power, when in the gap of the electromagnet is air and magnetorheological fluid. B_o – air environment; B_m – magnetorheological fluid environment

3.1. Experimental research methodology for MRF properties MRS

For the system operating in direct shear mode, when the side surfaces are not perform in other mode. In this case – valve mode. Contact element thickness is ultra-slim 0.2mm for that reason. This gives the cutting action skid surface during the investigation of magnetorheological fluid, when fluid viscosity is increasing. The other type of contacting elements of metrological values loses precise measurement values.



3.5 fig. Vertical section of immersed in a magnetorheological fluid contact element.

Contacting element moves at a given speed in a certain direction, and operates in a tensile force:

$$F_{stretching} = \frac{1}{2}\rho V^2 C_D 2S_{efect} \tag{3.1}$$

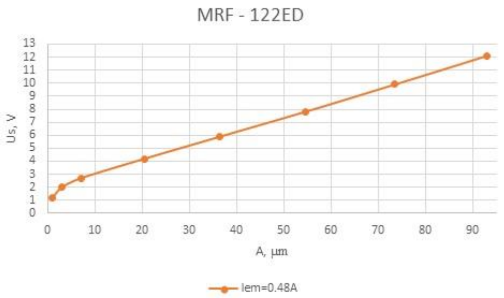
Here, ρ – density of the fluid; V – Speed of contact element; C_d – stretching factor; S_{efect} – effective area of the contact element.

Having, F_{temp} can be calculated shear stresses between two plates:

$$\tau = \frac{F_x}{S_{efect.}} \tag{3.2}$$

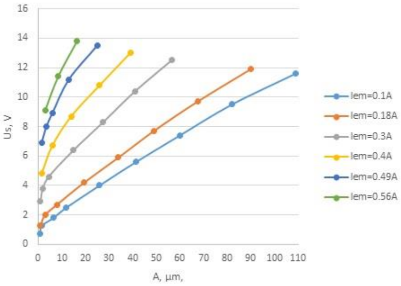
Contacting element selected is based on several factors. Size and shape already described, chosen by experimental fluid volume and magnetic conductor gap size, also the ability to fix contact element in right position. In addition, the small thickness of the contact element selected to obtain the effect of cutting, but not the valve operation when the moving plate is in the fluid. Material of contact element is cooper. Copper plate surface is polished. Copper is a non-magnetic material, which totally does not affect the magnetic field. It gives maximum direct shear effect, whereas the plate is smooth and the surface of the average arithmetic profile deviation RA8. This is perfectly in line with the quality requirements. When necessary smooth or extremely rough surfaces. In both of these cases, it reduces the direct shear effect size. When the surface is too smooth, fluid between the layers and contact element reduce the drag force. In the second case, when the surface of the contact would be too harsh, the magnetic fluid particles adhere to the contact element and resistance artificially increases, in both cases there is a gain of negative influence of experimental research results.

Everything starts from when the electromagnet poles are inserted into the vessel. Volume of vessel V=0.5 ml, filled with magnetorheological fluids, which is poured volume V=0.4ml. Using the stand double screw system, the piezoelectric actuator and contact element is immersed in the liquid under investigation allowable value. Start of experimental setup. In electromagnet windings flowing current, which has values vary from 0 A to 3 A, developing a magnetic field in the magnetorheological fluid. Viscosity of the fluid increases. Also, the piezoelectric actuator active layer is supplied voltage Uj that varies in the range of 0V to 160V. The active layer bends and at the same time the passive layer compresses. Compressive layer outputs result is generated signal voltage Us. That moment when the contact element starts to move is called shear yield strengthτ_y. Beyond a point of shear stress occurs when the adjacent fluid layers relative to each other moves. There is internal friction of the related layers that is directly proportional to the fluid viscosity. When the magnetorheological fluid is exposed to a stronger magnetic field, the friction between the adjacent liquid particles grows. There is a magnetorheological effect of the iron particles cling to each other and bound in chains. Contact element braking, performing resistant to movement. The calculations required τy value is found in accordance with the Bingham model. This value is located at a point after the bend curve and becomes a direct proportionality image (fig. 3.6). Therefore, the tangent is determined Us point to the τy value. The experimental primary objective is to determine the dynamic viscosity of the magnetorheological fluid detection methodology. In the same sequence it is possible to examine another important parameter rheological fluid - fluid density. During the experiments, when the piezoelectric actuator contact element is immersed with all effective area S_{efect} to the magnetorheological fluid. In such a way getting results. It is dependence between signal voltage Us in the passive layer and current I. Force voltage in active layer Uj=140V (fig. 3.6).



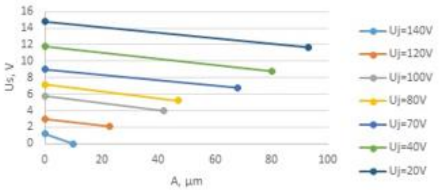
3.6 fig. Example, when signal voltage U_s known, and unknown and unknown yield strength stress value founding

The following uses the result obtained by measuring the amplitude of the piezoelectric actuator bending, under various experimental conditions. There are two large measurement range graphs, one of them measured relatively liquid (LORD company MRF – 122ED) and relatively dense (LORD company MRF – 140EG). Getting the extreme boundary conditions, the results of which consists of one common boundary condition, approximated curve. Two main curves, which will be useful in a following dynamic viscosity calculation methods steps.



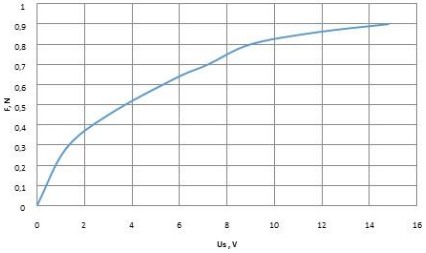
3.7 fig. Magnetorheological fluid MRF – 140CG piezoelectric actuator bending amplitude dependence to signal voltage Us

Summing approximation of the curves and the values, a single piezoelectric actuator sensor signal Us dependence on the amplitude schedule is observed, which is one of the main and supporting further steps.



3.8 fig. Boundary viscosities MRFresulting diagram

The second very important dependencies supporting schedule was obtained from an experimental study (fig. 3.9), when with the force measuring device MARK – 10 BGI measured the piezoelectric actuator blocking force to the corresponding signal values in the passive piezoelectric actuator layer.



3.9 fig. Piezoelectric actuator blocking force dependence on signal voltage Us.

The measurement of certain conditions, such as when choosing some kind of fluid, some force voltage Uj (V) – getting the result of a certain amount of signal voltage Us (V). Given the size of the voltage of the previously discussed dependencies achieves an amplitude A (µm) value, and some F (N) value. According to the Bingham model and its mathematical expression formula:

$$\tau = \tau_y + 2S\eta\dot{\gamma} \tag{3.3}$$

Here, τ – shear stresses; τ_y – yield stresses; 2S – effective contacting element area from both sides; $\dot{\gamma}$ – shear rate. With amplitude A value and blocking force F value calculating shear rate:

$$\dot{\gamma} = \frac{A \cdot 2\pi f}{h} \tag{3.4}$$

Here, f – frequency; h – distance between two planes (vessel wall and contacting element surface).The following is the yield stress calculation:

$$\frac{F}{2S} = \tau_y \tag{3.5}$$

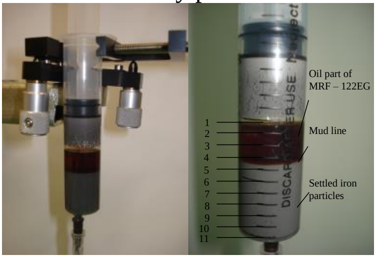
Finally, the magnetorheological fluid dynamic viscosity calculation:

$$\eta = \frac{\tau - \tau_y}{\dot{\gamma}} \tag{3.6}$$

Experimentally tested and developed a magnetorheological fluid dynamic viscosity test method. This section proposes a new test system, which is characterized by low price and compact composition, and the ability to locally measure the fluid. Researched magnetorheological fluid volume 0, 4 ml, which is poured into a copper 3,5ml width of vessel. Also in this section, the electromagnet magnetic properties are tested, with excellent results in line with expectations: $B_{analytical} = 1$ T ~ $B_{calculation} = 0.942$T ~ $B_{comsol\ modeled} = 1.15$T ~ $B_{experimental} = 0.95$T.

4. PIEZOELECTRIC DIAGNOSTIC SYSTEM FOR RHEOLOGICAL FLUIDS STABILITY SUPPORTING, CREATION

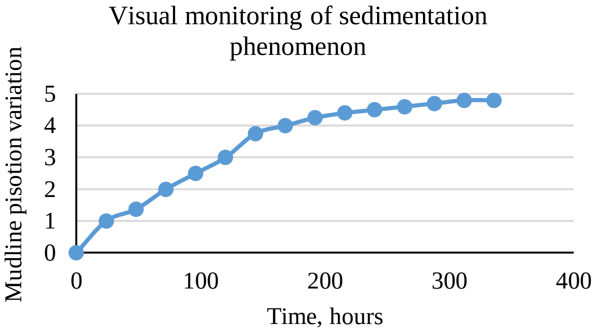
One of the important problems of rheological fluids – settling of ferromagnetic particles called sedimentation. Particles sedimentation influence the magnetorheological fluids application possibilities in devices. Stability of MRF depends on the particles size, density and viscosity. The simplest care of these fluids to avoid sedimentation is mechanical mixing. However, it is difficult to do in a device, in addition to being unreliable. In order to ascertain whether the fluid is stable, homogeny state and how long it is suitable for the use; certain tests were made, during which the required characteristics of the fluid were established. The experiments were performed using two fluids made in LORD company:MRF-140CG and MRF-122EG. One of the ways of mixing the fluids before it is used in an appropriate structure is a vibrating paint mixing stand. However, the researched case is specific and requires special mixing techniques. First of all, the sedimentation speed needs to be set by visual monitoring. Visual monitoring is suitable only when the fluid is not in any particular construction.



4.1 fig. Sedimentation phenomenon experimental stand

After the visual monitoring of magnetorheological fluid MRF – 122EG, sedimentation effect was identified, i.e. iron particles completely settles during 336 hours. Experimental vessel (fig. 4.1) divided in to eleven equal parts and mud line registration made every 24 hours.

4.2 Fig. shows sedimentation mud line position variation – This is the line that the situation is changing over time. This line is the boundary between the magnetic and non-magnetic part of the liquid. MRF was in a consistant state of the barrel in order to show a clear liquid sedimentation. Also, the inductance was measured at different fluid column heights in order to confirm the visual observation data. Inductive measurement method is determined by the concentration of magnetic particles at different levels of the column.



4.2 fig. The phenomenon of sedimentation curve

4.1. Magnetorheological fluid mixing using multifunctional electromagnetic system

Equipment for sedimentation measurements consists of a transparent tube containing a magnetorheological fluid and the induction coil, which is the basic unit of measurement. The magnetic induction measurement principle can establish the different levels of iron particles at different levels of the column because the magnetic induction is directly linked to the permeability constant.

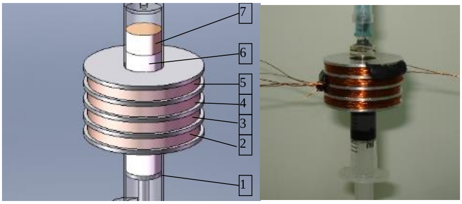
$$L = n^2 \cdot G \cdot \mu \tag{4.1}$$

n- The number of turns of the coil, G- geometric form coefficient, μ- magnetic permeability.

Inductance depends on the wire size and shape, as well as the environment in which the conductor of the magnetic properties:

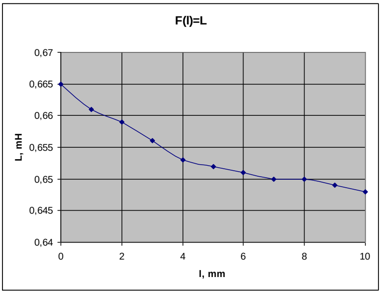
$$L = \frac{\phi}{I} \tag{4.2}$$

Here L- inductivity (H); ϕ - magnetic flux (Wb); I – current (A).



4.3 fig. MRF sedimentation measurement scheme. Design stand and the real view

The MR fluid particle concentration measurements found that increasing the concentration of particles in the induction coil - inductance decreases (4.4fig.). This is because the aluminum frame is solid and uncut, and it consists of an induction coil short circuited winding.



4.4 fig. Reels position dependence of inductors , sedimentation affected the MR fluid

After checking the MR fluid deposited particle concentration measurement method, it has been identified that it works. Therefore, a favorable construction can be widely used.

CONCLUSIONS:

1. After a detailed analysis of magnetorheological fluid and rheological parameters measuring device found that rheological parameters are being measured by a complex design rheometer, which often do not seek full magnetic induction, only to the B=0,3 T. For this reason, a mobile, small

construction and locally capable of measuring rheological parameters of magnetorheological fluids has been created. Which uses piezoelectric transducers operating on the direct and inverse piezoelectric effect.

2. Designed and manufactured specially shaped electromagnet for the magnetorheological fluid rheological parameters control. Which in Comsol Multiphysics 4.4 package was carried out the numerical simulations. Selected geometric dimensions and electromagnetic parameters of electromagnet allows experimental 0,4 ml magnetorheological fluid affect by magnetic field, whose magnetic induction changes from 0 to 1,2 T.
3. Using Comsol Multiphysics 4.4 package, accomplished numerical simulations of cantilever piezoelectric bimorph, the free end loaded of fluid viscosity strength. Established piezoelectric transducer dynamic characteristics, received excited displacement on the operating forces dependences and piezoelectric transducer generated electric signal dependences from the forces acting on the free end. Force and signal layer voltage ratio varies from 6.6 to 22 times, according to the magnetorheological fluid viscosity.
4. According to the simulation results, created magnetorheological fluids experimental stand for the rheological parameters setting, which used bimorph piezoelectric transducer (companyNoliac A/S), acting simultaneously in a direct and reverse piezo effect way. With experimental stand, investigated two types of magnetorheological fluids with a different rheology (company Lord: MRF – 122ED and MRF – 140 CG). An experimental research technique enabled by piezoelectric transducer generated electrical signal to determine the magnetorheological fluid rheological parameters, such as yield stress – τ_y and dynamic viscosity η. Calculated shear rate γ=5.26 (s^{-1}). Electromagnet develops maximum magnetic induction density in magnetorheological fluid area from 0T to 0, 98 T. An overall rheological parameters system testing, using laser displacement and strain gage force measuring devices. This test method is suitable in order to get quick information about the test fluid rheology. The experiment takes up to 30 minutes.
5. Created a magnetorheological fluid sedimentation monitoring and stability supporting devices using ultrasonic transducers and induction meter with a special probe. Experimentally determined that the phenomenon of sedimentation in magnetorheological fluid occurs within 336 hours. Inductivity measurement and stability supporting device is suitable for quick experimental results, also for permanent sedimentation phenomena monitoring.

List of publication

ARTICLES

Indexed in the Web of Science with Impact Factor

1. Ramutis Bansevičius, SigitaNavickaitė, Vytautas Jūrėnas, Viktorija Mačiukienė, Genadijus Kulvietis and Dalius Mažeika. *Piezoelectric laser beam deflector for space applications*. // Journal of Vibroengineering / Vibromechanika, Lithuanian Academy of Sciences, Kaunas University of Technology, Vilnius Gediminas Technical University. Vilnius : Vibromechanika. ISSN 1392-8716. JVE INTERNATIONAL LTD. JOURNAL OF VIBROENGINEERING. MAR 2016, VOL. 18, ISSUE 2. [Science Citation Index Expanded (Web of Science); INSPEC; Academic Search Complete; Computers & Applied Sciences Complete]. [Indėlis: 0,250]. [IF (E): 0,323 (2016)]
2. Bubulis, Algimantas; Jūrėnas, Vytautas; Navickaitė, Sigita and Rugaitytė, Viktorija. *Investigation of motion control of piezoelectric unimorph for laser shutter systems* // Journal of Vibroengineering / Vibromechanika, Lithuanian Academy of Sciences, Kaunas University of Technology, Vilnius Gediminas Technical University. Vilnius : Vibromechanika. ISSN 1392-8716. 2010, Vol. 12, no. 4, p. 533-540. [Science Citation Index Expanded (Web of Science); INSPEC; Academic Search Complete; Computers & Applied Sciences Complete]. [Indėlis: 0,250]. [IF (E): 0,323 (2010)]
3. Bansevičius, Ramutis Petras; Bubulis, Algimantas; Dragašius, Egidijus; Jūrėnas, Vytautas; Mačiukienė, Viktorija and Navickaitė, Sigita .*Control of piezoelectric scanner dynamics using magnetorheological fluid* // Journal of Vibroengineering / Vibromechanika, Lithuanian Academy of Sciences, Kaunas University of Technology, Vilnius Gediminas Technical University. Vilnius : Vibromechanika. ISSN 1392-8716. 2011, Vol. 13, no. 4, p. 755-763. [Science Citation Index Expanded (Web of Science); INSPEC; Academic Search Complete; Central & Eastern European Academic Source (CEEAS); Computers & Applied Sciences Complete; Current Abstracts; TOC Premier]. [Indėlis: 0,167]. [IF (E): 0,346 (2011)]
4. Dragašius, Egidijus; Jūrėnas, Vytautas; Mačiukienė, Viktorija and Navickaitė, Sigita. *Investigation of magneto-rheological fluid parameters using cantilever -type piezoactuator* // Journal of Vibroengineering / Vibromechanika, Lithuanian Academy of Sciences, Kaunas University of Technology, Vilnius Gediminas Technical University. Vilnius : Vibromechanika. ISSN 1392-8716. 2012, Vol. 14, no. 1, p. 189-195. [Science Citation Index Expanded (Web of Science); INSPEC; Academic Search Complete; Central & Eastern European Academic Source (CEEAS); Computers & Applied Sciences Complete; Current Abstracts; TOC Premier].

[Indėlis: 0,250]. [IF (E): 0,452 (2012)][Indėlisgrupėje: 0,667]Reports® Science Edition (Thomson Reuters, 2016)]. [Contribution: 0,250]

Scientific LR invention patent: "Pjezoelektrinė lazerio spindulio precizinio pozicionavimo pavara (G02B 27/62).

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Viktorija Mačiukienė was born on November 29, 1983 in Radviliškis. In 2002 she entered Kaunas University of Technology, the faculty of Mechanical engineering and Mechatronics. In 2006 she obtained a Bachelor of Sciences qualification degree in Mechanical Engineering. In 2008 she obtained a Master of Sciences qualification degree in Mechanical Engineering. From 2008 to 2012 studies in Kaunas University of Technology 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.

Pirmame skyriuje pateikta aktyviųjų reologinių skysčių analizė, išnagrinėti jų darbo režimai. Išsamiai išanalizuoti klampumo matavimo prietaisai bei smulkiai aptartos pjezoelektrinės medžiagos, pjezoelektriniai keitikliai.

Antras skyrius – tyrimų metodologija. Šiame skyriuje yra pateiktas skaitinis modeliavimas. Modeliavimas susideda iš dviejų dalių: elektromagneto ir pjezoelektrinio keitiklio tyrimas COMSOL programa.

Trečiasis darbo skyrius skirtas eksperimentiniams tyrimams. Jame pateikiami magnetoreologinio skysčio klampumo matavimo metodikos radimo eksperimentiniai tyrimai.

Ketvirtajame skyriuje pateikti pjezoelektrinės diagnostinės sistemos, reologinių skysčių ilgalaikiam stabilumui palaikyti eksperimentiniai tyrimai.

Kiekvieno skyriaus pabaigoje pateikiami apibendrinimai. Darbo pabaigoje suformuluojamos viso darbo išvados. Daktaro disertacijos apimtis 118 puslapių. Joje yra 115 paveikslų, 73 formulės ir 6 lentelės. Literatūros sąraše pateikti 88 literatūros šaltiniai.

Darbo tikslas ir uždaviniai

Šio disertacinio darbo tikslas – sukurti patikimą, mobilų patikros įrenginį galintį lokaliai nustatyti magnetoreologinių skysčių reologines savybes.

Šiam tikslui pasiekti iškelti tokie uždaviniai:

1. Atlikti literatūros ir patentinės medžiagos analizę magnetoreologinių skysčių tyrimo, monitoringo bei pritaikymo galimybių aspektais.
2. Suprojektuoti specialios formos elektromagnetą, kuris efektyviai keistų magnetoreologinio skysčio klampumą nuo pradinės B=0 T prie maksimaliai pasiekiamos magnetinės indukcijos B~1T ribos.
3. Baigtinių elementų metodu ištirti pjezoelektrinio keitiklio dinamines charakteristikas.
4. Sukurti ir eksperimentiškai ištirti magnetoreologinių skysčių reologinių parametrų nustatymo įrenginį.
5. Sukurti parametrų tyrimo prietaisą magnetoreologinių skysčių stabilumo palaikymui, panaudojant elektromagnetines rites bei pjezoelektrinius keitiklius.

Mokslinis naujumas

- Sukurti du reologinių skysčių homogeniškumo palaikymo būdai: elektromagnetinis ir pjezoelektrinis (ultragarsinis).
- Vienas iš sukurtų reologinių skysčių homogeniškumo palaikymo būdų yra daugiafunkcinis skirtas ne tik stabilumo palaikymui, bet ir magnetoreologinio skysčio monitoringui.
- Pjezoelektrinių medžiagų panaudojimas magnetoreologinio skysčio dinaminio klampumo vertei žinoti.
- Suprojektuota ir pagaminta nauja elektromagneto konstrukcija, kuri atitinka keliamus reikalavimus. Oro tarpelyje , tarp magneto polių, išvystomas magnetinės indukcijos dydis B lygus 1T.
- Sukurtas originalios konstrukcijos pjezoelektrinis keitiklis – jutiklis, kurio kontaktuojantis elementas, sąlyčio su magnetoreologiniu skysčiu metu, veikia tiesioginės šlyties režimu.

Praktinė vertė

Sukurtos dvi aktyvių skysčių reologinių savybių matavimo bei monitoringo sistemos. Viena jų daugiafunkcinė – skirta sedimentacijos reiškinio nustatymui ir pašalinimui. Kita, kuri yra pagrindinė disertacinio darbo dalis – magnetoreologinio skysčio dinaminio klampumo matavimo įrenginys. Naudojantis tokio tipo įrenginiais galima pakankamai tiksliai išmatuoti reologines savybes. Šių veiksmų pagrindiniai prietaisai ekonomine prasme vertinami teigiamai, kadangi jų praktinė vertė yra labai aukšta, o kaina žema. Atraminis palyginimas reometrai, kurių kaina yra santykinai labai aukšta lyginant su sukurtuoju įrenginiu.

Gynimui teikiami darbo rezultatai

1. Pjezoelektrinės diagnostinės sistemos magnetoreologinių skysčių ilgalaikiam stabilumui palaikyti darbinių charakteristikų tyrimai.
2. Magnetinių srautų pasiskirstymo magnetolaidyje tyrimo rezultatai.
3. Pjezoelektrinio keitiklio parinkimo tyrimo rezultatai.
4. Sukurto magnetoreologinio skysčio matavimo įrenginio testavimo rezultatai.

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