University of Pannonia
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Structure and mechatronic applications of electroreological and magnetoreological fluids

Ph.D. THESIS

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2023

Introduction

Intelligent or adaptive materials are a group of materials that change individual properties in a predetermined way in response to a given stimulus [1]. Electrorheological [ER] fluids, created by dispersing particles of higher permittivity in a liquid with low dielectric permittivity, were first described by Winslow in 1949 [2]. In these fluids, the change in viscosity results from a structural change in the dispersion. It can be observed that the electric field causes the particles to form pairs and then to form chains or columnar structures. The effect is reversible [3]. Electrorheological fluids are composed of a carrier and a dispersed phase, and may also contain additives, e.g. to increase stability [4]. Magnetorheological (MR) fluids are similar to electrorheological fluids in many properties and applications. Magnetorheological fluids are also smart materials with the special property of changing their rheological properties under the influence of an external magnetic field [5]. Jacob Rabinow [6] published a paper on MR fluids and their first applications, describing couplings using MR fluids. Magnetorheological fluids are prepared by dispersing soft magnetic particles with a diameter of micrometers into a liquid [7]. Due to their size, the particles are not monodomain, i.e. they have several magnetic domains and thus do not have an independent magnetic dipole moment. Magnetorheological fluids consist of a base fluid, or liquid phase, particles dispersed in it, or dispersed phase, and additives, similar to electrorheological fluids. The additives are mainly intended to prevent the particles from settling and agglomeration. The soft magnetic particles must not be allowed to aggregate to form larger particles, as this would accelerate settling and lead to a loss of stability of the system. Hence, unlike ER fluids, where a simple fluid can be created without surfactant or other additives, a surfactant is added to the simplest MR fluid containing silicone oil and magnetic particles [8].

The use of electrorheological fluids is based on their ability to reversibly change their apparent viscosity by an external electric field. In chemistry and biology, they can be used to target and retain active substances. In many cases, the variability of viscosity is used in the operation of torque-transmitting devices, brakes, shock absorbers and suspensions. Three basic technical uses of ER fluids have been identified: one in which shear of the fluid between surfaces is achieved; one in which the fluid affects flow by acting in a valve-like manner; and one in which the fluid is subjected to compression [9]. MR fluids have similar applications. Industrial uses include shock absorbers for buildings, vehicles, machine tools and bridges, brakes, and are also used as polishing agents [10]. Less common but applied uses are also known as chemical and optoelectronic sensors, in hydraulic valves and as sealants [11].

Aims

The utilization of soft intelligent fluids is influenced by the structure of the equipment used, therefore the aim of the research was to examine the parameters affecting the practical use. During the experimental work, three major goals were set. The forces acting in monodisperse and bidisperse chains will be examined. the heating of the sheared liquid under the influence of the field strength will be investigated. Magnetorheological clutches will be designed and built, and the magnitude of the transmitted torque and the torque transmission time constant will be measured.

Experiments

In the first part the forces acting in chains of electrorheological fluids are investigated, which are essential from the point of view of practical uses. During the theoretical research, I examined the forces acting in an infinite monodisperse chain, and then gave a closed formula for the forces acting in a monodisperse finite chain, as well as in bidisperse finite and infinite chains. In the case of a bidisperse chain, I derived the local field strengths in the chain, as well as investigated the change of the dielectric constant in ER fluids containing bidisperse chains.

In the second chapter, I researched the effect of temperature increase on the viscosity of electrorheological fluids. Based on measurements made on a rheometer, I modified the Andrade equation to give a correlation that describes the change in viscosity of electrorheological fluids as a function of temperature and electric field strength. I tested the formula on a mathematical model of the heating of an electrorheological clutch.

The third topic is the examination of the torque transmission time constant of magnetorheological clutches. After the design and construction of single-disc and multi-disc clutches, I examined the time constant of the single-disc clutch with unit jump excitation, and based on its mathematical model, I gave a relation for its description. In the case of a multi-disc clutch, I investigated the effect of ramp function excitation. The aim of the research was to describe the time constants as a function of the magnetic field, so that it can be controlled more precisely during practical use.

New scientific results, theses

1. Using theoretical calculations, the forces acting in finite and infinite chains of monodisperse and bidisperse electrorheological fluids, as well as the change of the dielectric constant in bidisperse chains were investigated. (Relevant publications: **[C2]**, **[K1]**)
   - **1.1.** A new relation for the internal electric field strength of a bidisperse chain was derived. Examining the local electric field strength in the ratio of the two particles of different sizes ($\sigma_B/\sigma_A = 1 \dots 10$) , the local field strength is found to increases more at the smaller particle.
   - **1.2.** Using the local field strength, the forces acting in the bidisperse chains were investigated. Similar to the monodisperse chains, it was found that, at low numbers of particles, the relation derived for the finite chains gives a lower value for the force than the one for the infinite bidisperse chains. The value of the forces acting in a bidisperse chain was found to be between the forces acting in monodisperse chains consisting of the particles making up the bidisperse chains.
   - **1.3.** I derived asymptotic equations for local field strengths in the limiting case $\sigma_B/\sigma_A \to \infty$. I have shown that the value calculated from the formulas introduced for the local field strengths of the bidisperse chain agrees with the results of the limit calculation
   - **1.4.** Starting from the Clausius-Mosotti equation, the change of the dielectric constant in bidisperse chains was investigated using two different concentrations. The change in the dielectric constant in mixed, bidisperse chains is found to be between the changes observed in the case of monodisperse chains consisting of bidisperse chains' constituent particles.

2. Based on measurements performed on an Anton Paar Physica MCR301 rotational viscometer, A new correlation for the temperature and field strength dependence of the viscosity of electrorheological fluids were introduced by expanding the Andrade equation. (Relevant publications: **[K2]**, **[K4]**)
   - **2.1.** The viscosity of ER fluid made of silicon dioxide powder and silicone oil, with three different concentrations (10, 20 and 30 m/m%) were measured in a temperate environment, from temperature T = 293 K to temperature T = 343 K. The applied electric field strength was varied between 0 and 1769 kV/m. Comparing the measurement results with the results calculated with the newly introduced relation, it was found that the new formula describes the temperature and field strength dependence of viscosity well, the average value of the deviations is 1.26% at 10% dispersion, 3.02% at 20%, 2.73% for a 30% dispersion.
   - **2.2.** Using the introduced correlation, the temperature rise of a theoretical ER clutch model was examined. For the model, the data h = 0.04 m, r = 0.0133 m, s = 0.0113 m, ω = 4.057 rad/s and C = 0.05 J/K were used. The differential equation created as a description of the temperature change was solved both numerically and analytically using series analysis. It was found that the value obtained in the numerical calculation can already be obtained by taking into account the first 5 members of the series analysis. The heating to the same temperature is found to occur faster with increasing concentration and field strength.

3. The torque transmission and torque transmission time constants of self-developed single-disc and multi-disc MR clutches were investigated with different MR fluids and excitations. (Relevant publications: **[C1]**, **[K3]**)

3.1. Lord MRF-122EG, MRF-132DG, MRF-140CG and 190521-1+20Fe fluids were tested in a single-disc MR clutch at speeds of 11.5 to 46.5 1/min and magnetic field strengths of 91 to 155 kA/m. Using unit jump excitation, the torque transmission time constants were determined for the examined parameters and fluids.

The torque transmission time constants in the case of a single-disc clutch were found to depend only slightly on the speed. As the magnetic field strength increases the value of the time constants shows either a decreasing trend or an increase after a decreasing phase depending on the speed and the applied liquid.

3.2. In the case of the multi-disc clutch, it was found that due to the multiple layers of fluid, the transferable torque is greater using the same magnetic field strength as in the case of a single-disc clutch. I show that the ramp function method is suitable for determining the torque transmission time delay of MR clutches.

Using a ramp function, the time delays were found to decrease as the slope of the ramp increases, while it depends little on the speed. Dividing the total time delay into mechanical, electronic and liquid time constants parts, it was established that the mechanical and electronic time constant are independent of the slope of the applied ramp function, but they influence the total time delay.

Scientific publications, presentations and posters for the basis of theses

[C1] **Mester, S**.; Horváth, B., Lukács, A. and Szalai, I.: Investigation of the torque transmission time constant of a multi-disc magnetorheological clutch in the case of ramp function excitation, IOP Conference Series: Materials Science and Engineering (1757-8981 1757-899X): 1246 1 p. 012005. (2022)
https://doi.org/10.1088/1757-899X/1246/1/012005

[C2] **Mester, S**.; Horváth, B. and Szalai, I.: Polarizabilities and electric field-induced forces in periodic two-component linear dielectric sphere chains, Journal of Molecular Liquids

[C3] **Mester, S.** and Szalai, I.: Temperature and Electric Field Dependence of the Viscosity of Electrorheological (ER) Fluids: Warming up of an Electrorheological Clutch, Hungarian Journal of Industry and Chemistry (0133-0276 2450-5102): 48 2 pp 59-64 (2020) https://doi.org/10.33927/hjic-2020-29

[K1] **Mester, S.** és Szalai, I.: Az elektroreológiai folyadékok alkalmazása felületi megmunkálásra: a láncképződés vizsgálata, In: Biró, K Á; Sebestyén, P Gy (szerk.) ENELKO 2016 - XVII. Nemzetközi Energetika-Elektrotechnika Konferencia, SzámOkt 2016 - XXVI. Nemzetközi Számítástechnika és Oktatás Konferencia, Erdélyi Magyar Műszaki Tudományos Társaság (EMT), (2016) pp. 94-98., 5 p., ENELKO, Kolozsvár, Románia, 2016. október 6-9.

[K2] **Mester, S.** és Szalai, I.: Elektroreológiai folyadékok viszkozitásának hőmérséklet- és térerősség függése, In: Bíró Károly-Ágoston ; Sebestyén-Pál György (szerk.) ENELKO 2017: XVIII. Energetika-Elektrotechnika Konferencia, SzámOkt 2017: XVII. Nemzetközi Számítástechnika és Oktatás Konferencia, Erdélyi Magyar Műszaki Tudományos Társaság (EMT), (2017) pp. 77-82., 6p., ENELKO, Nagyvárad, Románia, 2017. október 12-15.

[K3] **Mester, S**. és Szalai I.: Magnetoregolóiai tengelykapcsoló nyomatékátviteli időállandójának vizsgálata, In: Barabás, István (szerk.) XXVII. Nemzetközi Gépészeti Konferencia OGÉT 2019,: Erdélyi Magyar Tudományos Társaság (EMT), (2019) pp. 348-351., 4 p. Nagyvárad, Románia, 2019. április 25-28.

Other scientific publications, presentations

1. Decsi, P.; Bors, Á.; Kocsor, P.; Vörös, B.; Horváth, B.; Guba, S.; Gugolya, Z.; **Mester, S.**; Szalai, I.; A Framework for Demonstration Devices Used in Distance-Learning Environments, Hungarian Journal of Industry and Chemistry, 49 (1) pp 17-21 (2021)
   DOI: https://doi.org/10.33927/hjic-2021-03
2. **Mester, S.** and Szalai, I: Torque Transmission Time-Constant Examination of a Disk-Type Magnetorheological Clutch, Hungarian Journal of Industry and Chemistry, 48 (2) pp 59-64 (2020)
   DOI: https://doi.org/10.33927/hjic-2020-12
3. Decsi, P.; **Mester, S.** and Szalai, I.: Tárcsás magnetoreológiai tengelykapcsoló modellezése, a rendszer időbeli viselkedésének vizsgálata, In: Barabás, István (szerk.) XXVI. Nemzetközi Gépészeti Konferencia OGÉT 2018,: Erdélyi Magyar Tudományos Társaság (EMT), (2018) pp. 91-94., 4 p. Marosvásárhely, Románia, 2018. április 26-29.
4. Kapuváry, B.; Molnár, G; **Mester, S.**; Horváth, B. and Szalai, I.: Magnetoreológiai tengelykapcsoló tervezése, építése és nyomatékátvitelének vizsgálata, In: Barabás, István (szerk.) XXVI. Nemzetközi Gépészeti Konferencia OGÉT 2018,: Erdélyi Magyar Tudományos Társaság (EMT), (2018) pp. 236-239., 4 p. Marosvásárhely, Románia, 2018. április 26-29.

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