Dynamics of Magnetic Fluid Cylinder in Inhomogeneous Magnetic Field

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Abstract. The dynamics of some magnetic fluid (MF) samples of various concentrations filling the tube horizontally and held by a field of a magnetic axial system made based on unipolar permanent rare-earth ring magnets were studied. The magnetic field of an "axial" magnetic system of MSO was studied, as well as the dependence of the system oscillation frequency on the length of the MF cylinder. An original method for determining MF magnetization is proposed and applied to the obtained data. Magnetization was determined for three magnetic fluid samples. The results obtained by the developed method are comparable to the magnetization values obtained by the ballistic method. The developed and presented technique of a dynamic experiment with measuring oscillations frequency of the "MF column suspended in a strong and inhomogeneous magnetic field" system involves the creation of a new absolute method for determining saturation magnetization and can be useful for studying magnetophoresis and aggregation processes of magnetic nanoparticles. This technique is used to study the degree of elastomagnetic consistency parameters over time.

1. Introduction
Magnetic fluid is a unique material that combines a rich set of physical, mechanical, and physicochemical properties of fluid medium with a strong response to a magnetic field. All this allows MF to be used as an active element, physical parameters of which can be controlled by means of an external magnetic field. These features made it possible to create a wide range of devices and instruments for quenching vibrations, acoustic speakers, various sensor systems based on MF [1-6]. The main characteristics that determine magnetic fluid properties are magnetization and viscosity, as well as their dependence on the external magnetic field [7-9]. Nowadays, there is a sufficiently rich set of methods to determine these characteristics. These methods can be used for studying liquid's response to various external influences: variable bias field, vibration, rotation in a magnetic field. However, the cylinder is often an active element in the majority of MF-based devices (shock absorbers, dampers, ferrofluid seals, sensors). This MF cylinder is in an almost saturated state and it makes oscillatory motions. Therefore, it seems relevant to study the dependence of magnetization on the strength of an external magnetic field in magnetic systems based on permanent magnets allowing long exposure of the sample in the system.

2. Magnetic system
In the research article [10], an option of determining MF magnetization in the magnetic field of a laboratory magnet FL-1 based on the static and dynamic experiment is proposed. The laboratory setup is quite massive, electromagnet FL-1 is an expensive device and requires a constant connection to a power source, which makes it difficult to perform long (several hours and days) experiments. There is a high risk of failure of the experiment due to power loss. A system based on permanent magnets does not have such shortcomings. But until recently it has not been possible to achieve field values in them that exceed 1 T. This drawback has been eliminated with the advent of axisymmetric step-type magnetic systems using unipolar ring magnets. Such systems have been described for the first time in the
theoretical works of H. A. Leupold [11, 12]. In Russia, the production of such systems was established at POZ-Progress LLC, Verkhnyaya Pyshma [13], where a magnetic axial system MSO based on an assembly with rare-earth magnets NdFeB (neodymium-iron-boron) was ordered. It is shown in Figure 1a. The setup presented in Figure 1b was made to measure the magnetic field. A microscrew-based precision movement system with a step motor controlled by a microcontroller was used to move the sensor element of the milliteslometer (Hall sensor).

Results of magnetic field scanning are in Figure 2 in the form of dependence of magnetic field strength on distance from the pole center of axial magnetic system.

Based on the data presented in Figure 2, the intensity gradient is calculated according to the formula for MSO magnetic system. Obtained magnetic parameters are given in Table 1.

Analysis of the presented data reveals the following characteristic features of the magnetic field of the axial magnetic system based on the set-up with rare-earth magnets NdFeB. First, the magnetic field should be noted symmetrically relative to the Z-axis. It can be seen from Table 1 that this magnetic system is characterized by a linear dependence of the gradient on the coordinate at a distance from 0 to 27.5 mm from the center. There is an area with a constant gradient value at 27.5-42.5 mm from the center. The gradient decreases according to a linear law from 42.5 mm to 75 mm. Obtained functions show that axial magnetic system can be used to study active multiphase magnetic systems in increasing,
constant and decreasing gradients of the magnetic field. This makes such a system unique in the combination with the possibility of conducting long-term experiments.

### Table 1. Calculation of magnetic system field strength gradient

| $H_1$, kA/m | $H_2$, kA/m | $z_1$, mm | $z_2$, mm | $\Delta H/\Delta z$, MA/m² |
|-------------|-------------|------------|------------|----------------------------|
| 433         | 430         | 5          | 0          | 0.7                        |
| 430         | 418         | 10         | 5          | 2.4                        |
| 418         | 399         | 15         | 10         | 4.1                        |
| 399         | 367         | 20         | 15         | 6.6                        |
| 367         | 327         | 25         | 20         | 8.4                        |
| 327         | 270         | 30         | 25         | 10.9                       |
| 270         | 215         | 35         | 30         | 10.9                       |
| 215         | 152         | 40         | 35         | 10.9                       |
| 152         | 102         | 45         | 40         | 10.9                       |
| 102         | 59          | 50         | 45         | 8.7                        |
| 59          | 33          | 55         | 50         | 5.3                        |
| 33          | 10          | 60         | 55         | 4.6                        |
| 10          | 3           | 65         | 60         | 0.8                        |
| 3           | 1           | 70         | 65         | 0.4                        |
| 1           | 0.4         | 75         | 70         | 0.2                        |
| 0.4         | 0.06        | 80         | 75         | 0.1                        |

### 3. Experimental setup and physical parameters of samples

Experimental data were obtained on samples of MF. These samples are stable colloidal solutions of single-domain particles of magnetite Fe₃O₄ which are stabilized with oleic acid, in a hydrocarbon (kerosene, mineral oil) medium.

The original sample of MF-1 was synthesized in ISPU SRL of applied ferrohydrodynamics. MF-2 and MF-3 samples were obtained by diluting the starting sample of MF-1 to a solid concentration of 6% and 4%, respectively. The physical properties of the samples are shown in Table 2.

### Table 2. Physical properties of MF samples

|               | MF-1 | MF-2 | MF-3 |
|---------------|------|------|------|
| MF density $\rho$, kg/m³ | 1245 | 1058 | 952  |
| Volume concentration $\varphi$, % | 10.56 | 6.32 | 3.93 |
| Saturation magnetization $M_s$, kA/m | 43.3 | 20.7 | 12.9 |
| MF viscosity, mPa·s | 31.8 | 4.15 | 2.45 |

Figure 3 shows the appearance and flowchart of the experimental setup.

A glass tube with the following dimensions was placed between the magnet poles: the outer diameter is 16 mm; the length is 255 mm; the inner diameter is 14 mm. The tube is filled with MF to a column height of 7 cm.

The MF column retains the shape of the cylinder and is held in the equilibrium position by the magnetic levitation effect. Vibrations of the MF column are excited by pulling out the rubber plug with the hole. Air cavity is present between the free surface of MF and the plug. A pressure jump in the gas cavity occurs when pulling out a plug with a closed hole from the tube. Both ends of the tube remain open during vibrations of the MF column.

For the same value of magnetic fluid volume in the tube, the oscillation experiment was conducted at least three times. MF oscillation frequency values were taken as average values. Then, some amount of magnetic fluid was taken from the tube using a syringe so that the length of the column was reduced.
by 0.5 cm. Similar actions were carried out until the length of the column was reduced to 2 cm with a step of 0.5 cm.

**Figure 3.** Experimental setup: (a) general view, (b) block diagram (top view), where 1 - magnetic axial system; 2 - transparent tube of plated glass; 3 - LED tape; 4 - magnetic fluid; 5 - inductance coil; 6 - signal amplifier Selective Nanovoltmetertype 237; 7 - oscilloscope GwInstek GDS-72072; 8 - tube holders; 9 - rubber plug

### 4. Experiment and its interpretation

An array of frequency data of the MF column was obtained depending on its size for all three samples. It was done by using LabView program. The results are shown in Table 3.

**Table 3.** Frequency of MF column oscillations depending on its size

| Column, b, cm | Frequency, v, Hz |
|--------------|-----------------|
|              | MF-1 | MF-2 | MF-3 |
| 7            | 14.55 | 13.88 | 11.21 |
| 6.5          | 15.29 | 13.98 | 11.49 |
| 6            | 15.81 | 14.03 | 11.62 |
| 5.5          | 15.96 | 13.96 | 11.61 |
| 5            | 15.99 | 13.81 | 11.51 |
| 4.5          | 15.97 | 13.69 | 11.28 |
| 4            | 15.96 | 13.47 | 11.16 |
| 3.5          | 15.8  | 13.3  | 11.02 |
| 3            | 15.6  | 12.87 | 10.82 |
| 2.5          | 15.15 | 12.68 | 10.69 |
| 2            | 14.94 | 12.54 | 10.37 |

Based on the experimental data presented in Tables 1-3, the magnetization value of MF was determined by using the formula proposed in [14]:

$$M_s = \frac{\pi^2 v \rho bd^2}{\mu_0} + bf \sqrt{\pi^2 v \eta \rho}$$

Obtained data are shown in Figure 4 in comparison with magnetization data of each MF sample obtained by ballistic method considering the field gradient of the magnetic system.
Figure 4. Comparative analysis of the obtained data (solid markers: theoretical calculation based on the present experimental data; empty markers: magnetization data obtained by the ballistic method)

The graphs show satisfactory agreement between experimental and calculated data within the uncertainty of measurements.

5. Conclusion
A dynamic experiment technique based on measuring the frequency of oscillations of MF cylinder levitating in a strong inhomogeneous magnetic field has been developed. It can be used to study the stability of elastomagnetic parameters over time. It is possible to create a new absolute method for determining the saturated magnetization and monitoring the change in physical parameters of magnetic fluid with long exposure in inhomogeneous magnetic fields according to the conducted studies. The results can be useful for investigating the aggregation processes of magnetic nanoparticles and magnetophoresis.

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