Magnetorheological gel-based magnetoresistor: Effects of a static and a periodic time-varying magnetic field on the electrical resistance

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Abstract. A magnetoresistor having as resistive element a magnetorheological gel (MG) based on silicone rubber and Fe microparticles is fabricated. An experimental setup is built and described for measuring the electrical resistance \( R \) of the magnetoresistor in a static and in a periodic time-varying magnetic field (PTVMF). The results show that the resistance is significantly influenced by increasing the magnetic flux density, and the PTVMF induces transient processes inside the magnetoresistor. We explain these processes.

1. Introduction
Magnetorheological materials (MRSs) are smart materials which the property that their physical characteristics can be controlled when an external magnetic field is applied [1–6]. The main classes of such materials are magnetorheological suspensions (MRSs), elastomers (MREs) and gels (MRGs). Due to their large fields of applications in which they can be used, in recent years these materials have received an increased interest from both academic and industrial communities alike.

Thus, in Ref. [1] a MRSs has been successfully fabricated by the thermal decomposition of Fe₂(CO)₉ particles in silicone oil (SO), and the influence of the thermal regime on the particle dimensions has been established. The main applications envisioned for this type of MRSs are in fabrication of magnetically controlled vibration dumpers and clutches. In Refs. [2] it is shown that the features required by these devices can be fulfilled by increasing the magnetic field intensity, since under these conditions the apparent viscosity of MRSs can be changed very fast. In addition, when the MRSs is based on carbonyl iron (CI) and SO the electrical conductivity and thermal conductibility can be controlled by using graphite microparticles [3, 4] and/or by modification of the volume fraction of CI inside the liquid matrix of MRSs [5–7]. More recently, ecologically friendly and low-cost MRSs have been manufactured by replacing SO with honey bee, and it has been shown that their electrical properties and the magnetodielectric effects induced by the magnetic field makes them usefull for biomedical applications [8, 9]. Fabrication of composite materials based on MRSs has been successfully realized by soaking them in fabrics made from natural polymers. Thus, active magnetic tissues have been manufactured with remarkable electrical and dielectric properties [10, 11].

In MREs the magnetizable phase consists from ferro/ferri-magnetic nano/micro-particles dispersed in an elastic matrix. In a magnetic field the visco-elastic properties are changed due to the reordering
of the particles forming the magnetic phase \[12,13\]. Their electroconductive, magnetodielectric and viscoelastic properties are sensibly influenced mainly by the applied magnetic field and by additives \[14-23\]. These features make them useful for fabrication of magnetic field, mechanical or deformation sensors \[14-17\]. Such a large spectrum of applications usually require a detailed description of the structural properties at nano- and micro-scales. Generally such information is obtained by using small-angle scattering methods (neutrons or x-rays, depending on the information sought), computed tomography or electron microscopy \[24-26\]. Of particular interest are the interaction processes between microparticles, on one hand, and the elastic matrix, on another hand, as well as the size, shape and organization of microparticles inside the matrix. Since quite often the microparticles form complex aggregates, fractal-based models are found to be very useful for description of their properties \[27\].

In the case of MRG relatively less studies have been performed, probably due to an insufficient understanding of the interplay between the matrix gel and magnetic fillers. However, due to the property of the embedding fluid to be gellated, MRG can be very useful in applications which require more than a single stimulus, such as a magnetic field together with temperature or pressure. Thus, in this work we present a new method for preparation of a magnetoresistor based on MRG. We present and describe an experimental setup used for testing the magnetoresistor in a static and a periodic time-varying magnetic field (PTVMF). We show that the electrical resistance of the magnetoresistor increases with increasing the magnetic flux density of an external magnetic field. In a PTVMF, the resistance changes by closely following the time-variation of the magnetic field. We explain the observed effects through the reordering of magnetic dipoles along the magnetic field lines.

2. Fabrication of the magnetoresistor

The materials used for fabrication of magnetoresistor are Fe microparticles (\(\mu Fe\)) from Merck, with diameters between 4.5 and 5 \(\mu m\) and density \(\rho = 7.89 \text{ kg/m}^3\), liquid silicone rubber (SR), RTV 3325 type from Bluestar Silicone Commerciale SpA, with viscosity 250 mPa \(\times\) s at 25\(^\circ\)C, omnifex syringe (BS) with a volume of 1 ml from Polymed and a copper conductor (CW) MFY type with a diameter of 2.5 mm from Atu. Tech. Fabrication of the magnetoresistor consists in the following steps:

- A volume of 2.4 \(\text{cm}^3\) of \(\mu Fe\) is mixed with 1.6 \(\text{cm}^3\) SR at 120\(^\circ\)C for about 240 s. After the source heat is removed, the homogenization continues until the temperature of the mixture becomes about 22\(^\circ\)C. At the end of this step one obtains a composite material, called MRG.
- BS are cut in the shape of tubes with length of 35 mm.
- Stoppers are fabricated from CW with dimensions 4 mm \(\times\) 10 mm.
- At one end of BS tube is attached one stopper from CW, and at the other end is introduced MRG. At the end of this operation the second stopper is fixed. The distance between stoppers is fixed at \(l = 5\) mm. At the end of this step one obtains an electrical device which is a magnetoresistor, with the overall configuration shown in Fig. 1 left part, and photo in Fig. 1 right part.

![Figure 1](image-url)

**Figure 1.** (Color online) Left part: Overall configuration of the magnetoresistor: 1 - MG, 2 - copper stopper, \(D\) - MG diameter, \(l\) - MG length. Right part: Photo of the magnetoresistor: 1 - BS, 2 - copper electrodes.
3. Testing the magnetoresistor

The experimental setup used for performing the magnetic characterization and studying the response of magnetoresistor is shown in Fig. 2(a), and consists from an electromagnet and a continuous source (not shown in Fig. 2(a)), a Gaussmeter with a hall probe and an RLC bridge connected to a computing unit (also not shown in Fig. 2(a)). The magnetoresistor is fixed between the N and S poles of the electromagnet, where the magnetic flux density is fixed by the intensity of electric current from the source and is measured with a hall probe \( h \). The electromagnet coil has the resistance \( R_L = 5.8 \, \Omega \) and inductance \( L = 21 \, \text{mH} \). The resistance \( R \) of magnetoresistor is measured with a precision of \( \pm 4\% \) with a bridge Br 8646-type from Fluke, at time intervals of 1 s. Generally this RLC bridge can measure electrical resistances from 10 \( \Omega \) to 1000 \( \text{M} \Omega \). The obtained data from Br are recorded by the computing unit and analyzed with a dedicated software program for RS232 interfaces. The resistance is measured both in a static and a PTVMF with amplitudes of 100, 200, 300 and respectively 400 mT, and a period of 120 s.

4. Theoretical model

A model of the distribution of magnetic dipoles inside SR is shown in Fig. 2(b). We consider here that they arranged in aggregates forming parallel chains. After time \( t \) since application of the magnetic field, the distance between dipole centers is given by \([8–11]\):

\[
x = \frac{d}{\sqrt[3]{\Phi}} \left( 1 - \frac{1.25 \sqrt[3]{\Phi} B^2}{\mu_0 \eta} t \right),
\]

(1)

where \( d \) and \( \Phi \) are the diameter and respectively the volume fraction of \( \mu Fe \), \( B \) is the magnetic flux density, \( \mu_0 \) is the magnetic constant vacuum, and \( \eta \) is the apparent viscosity of MRG.

From an electrical point of view two neighboring and identical dipoles form a linear microresistor with resistance \( R_{x1} \), which can be approximated by:

\[
R_{x1} \simeq \frac{4x}{\pi \sigma d^2} \quad \text{at} \quad B \neq 0, \quad \text{and} \quad t > 0,
\]

(2)

where \( \sigma \) is the electrical conductivity, and \( d \) is the diameter of magnetic dipoles. Then, a chain of magnetic dipoles has the resistance \( R_x \), which can be approximated by:

\[
R_x \equiv N_1 R_{x1} = \frac{4lx}{\pi \sigma d^3},
\]

(3)

where \( N_1 \gg 1 \) is the number of magnetic dipoles inside the chain. Thus, the total number of magnetic dipole chains can be obtained from:

\[
N_2 \equiv \frac{N}{N_1} = \frac{3D^2 \Phi}{d^2},
\]

(4)

where \( N \) is the number of magnetic dipoles from MRG. Therefore, by using Eqs. (1), (3) and (4), the electrical resistance of the magnetoresistor becomes:

\[
R \equiv \frac{R_x}{N_2} = \frac{8l}{3\pi \sigma D^2 \Phi} \left( 1 - \frac{1.25 \sqrt[3]{\Phi} B^2}{\mu_0 \eta} t \right)^{1/5},
\]

(5)

from which we obtain the apparent viscosity \( \eta \) according to:

\[
\eta = \frac{1.35 \sqrt[3]{\Phi} B^2 t}{\mu_0 \left( 1 - (R/R_0)^5 \right)},
\]

(6)

where \( R_0 \) is the electrical resistance of the magnetoresistor at \( B = 0 \).
5. Experimental results and discussions

The magnetoresistor (DE) is introduced between the N and S poles of the electromagnet shown in Fig. 2(a), and the resistance $R$ is measured with the help of the RLC bridge, for fixed values of magnetic flux densities. During the measurements we observe that in the absence of magnetic field, that is at $B_0$, $R$ has finite values, as shown in Fig. 3(a) black - squares. Distinct values of the resistance, as compared to those at $B_0$, are obtained when $B \gtrsim 100$ mT, as shown in Fig. 3(a) red - squares ($B = 100$ mT), blue - up triangles ($B = 200$ mT), magenta - down triangles ($B = 300$ mT) and olive - rhombus ($B = 400$ mT). The variation of $R$ with $t$ has a quasi-linear behaviour at each value of $B$. However, for a fixed value of $t$, $R$ decreases with increasing $B$.

In a PTVMF, the variation of resistance is presented in Fig. 3(b). The results show that when the magnetic field is switched on, the variation of $R$ with $t$ at a fixed $B$, that is the curve $R = R(t)_B$ is similar to the behaviour of $B$ with $t$. However, when the magnetic field is switched off, transient processes occur inside MRG sue to its apparent viscosity, as we shall see below. They are reflected in the curve $R = R(t)_B$ through increasing values between two successive moments when $B$ is switched on.

By introducing numerical values $\Phi_{Fe} = 60$ % vol. conc., $\mu_0 = 12.56 \times 10^{-7}$ H/m, and $t = 120$ s in Eq. (6), one obtains:

$$\eta = \frac{842.4B^2(\text{mT})}{1 - (R/R_0)^5}. \quad (7)$$

By using the numerical values of $R = R(t)_B$ from Fig. 3(b) in Eq. (7) one can clearly see in Fig. 4(a) and (b) that the functions $\eta = \eta(t)_B$ have also a behaviour similar to variation of $B$ with $t$, as shown in Fig. 2(b). This shows that the transient processes occur due to the alignment of the magnetic dipoles along the magnetic field lines, with direct effects on the apparent viscosity \cite{28, 29}.

6. Conclusion

In this work we present the manufacturing process of a MRG based on liquid SR and Fe microparticles. The obtained MRG is used as a resistive element for fabrication of a magnetoresistor. We show that in a
constant magnetic field as well as in a PTVMF, the resistance of the magnetoresistor can be controlled in the presence of an external magnetic field with magnetic flux densities between 100 and 400 mT. We also show that the variation of the resistance with time, closely resemble the variation of magnetic flux density with time, and transient processes occur in the magnetoresistor. By using the model of dipolar approximation these processes are attribute to changes of apparent viscosity in MRG, induced by the magnetic field density.

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