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An inductance-based technique for the measurement of magnetic moment of the magnetorheological fluids

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ABSTRACT

We presented a detailed study of the inductance properties of a MRF-based system with different MRF volume fractions under a magnetic field. The inductance of the system raised firstly and then decreased while the magnetic field kept increasing. We theoretically analyzed the mechanism of the field-induced variation of the inductance and deduced that the magnetic field dependence of the inductance could be represented by the derivative of the magnetic moment of MRF, thus the *M*–*H* curves of the MRF could be derived from the inductance measurement proceeded in our work. This method for the magnetization calibration was very convenient and economic for manipulation compared with the traditional magnetization meter techniques and has been proved to be feasible according to the experimental results which showed a satisfactory measurement precision.

1. Introduction

Magnetorheological fluids (MRF) are mainly dispersion of micro-scale particles made of soft magnetic materials in a non-magnetic carrier oil [1–3]. Upon application of a magnetic field, the ferromagnetic particles will form string-like structures parallel to the magnetic flux line [4]. In this chaining process, the yield stress and the viscosity of the system will change and show a significant dependence on the external magnetic field. This reversibly controllable flowability of MRF makes it a new generation intelligent material and have been exploited for use in a variety of devices such as automobile suspensions system [5–7], mechanical dampers [4], and bridge-stay cables [8]. Moreover, a strong growth in the future application of the MRF-based equipments has been anticipated [9], thus the researches on the conductive and flowability properties of MRF have been a hot spot recently.

As a kind of special magnetic material, MRF are usually studied by the measurement of the *M*–*H* curves to characterize the sample's magnetization state under the external magnetic field which is deeply related with the performance of the MRF-based apparatus. The magnetization property of MRF, which is critical for the performance of the related apparatus worked in a magnetic field, are related to many factors such as the size, the type and the volume fraction of the ferromagnetic particles [10–12]. However, in most laboratories, the magnetization curves of the MRF were mostly obtained by the traditional scientific magnetic equipments like SQUID (Superconductivity Quantum Interference Device) or VSM (Vibrating Sample Magnetometer) [13,14], which are mainly designed for the film-materials and are expensive for purchasing and running, also the volume of the samples to be tested should be very small in order to be fastened in the measurement apparatus. These seriously limited the experimental works on the researches of MRF.

In this paper, we reported on the measurement of the inductance of a coil system with a magnetic core of MRF under a magnetic field. By studying and analysing the inductance response to the magnetic field, we proposed a

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more effective approach to measure the MRF moment dependence on the magnetic field. Although the principle for this technique has been advanced for decades [15], it failed to cause enough attention and rarely be used in the measurement for MRF. We studied this method in detail in our work and obtained the *M–H* curves of the MRF. The results proved that our technique is much more convenient and economical compared with the traditional methods for the MRF measurement. In addition, it was also suitable for other liquid materials and bulk materials with big volume. Also, the inductance property of our MRF-based system could be taken into application of the intelligent electrical sensing devices.

2. Experimental device and measurement principle

The version of MRF we used in the experiments was J01T, which was obtained from Chongqing Material Research Institute. The ferromagnetic particles of the MRF are Fe_3O_4 powders and the mean diameter of them was about 10 μm. Same experiments have been proceeded on MRF with different volume fractions of 10%, 25% and 35%, respectively. As the magnetic core, the MRF were injected into a home-made columnar container which was set into a coil, then the inductance of the coil was measured by a digital inductance meter (version of ELC-120LCR). The diameter of the bottom side and the length of the container were 10 mm and 12 mm. The external magnetic field was applied alone the axial direction of the coil and the maximum magnetic field was 0.7 T. Fig. 1 shows the schematic of our measurement system and the picture of our MRF container for the inductance measurement.

In a physical view, the inductance of the coil system is originated from the change of the magnetic flux induced by the change of the current through the coil, the inductance could be expressed as:

$$L = d\psi/dI = d(\psi_1 + \psi_2 + \psi_3)/dI \tag{1}$$

Here I is the induction current and ψ is the magnetic flux, which could be divided into three parts: ψ_1, the magnetic flux contributed by the coil itself when a current is applied; ψ_2, the magnetic flux contributed by the MRF magnetic core and ψ_3, the magnetic flux contributed by the external field. So $L_1 = d\psi_1/dI$ is the coil's inductance, which is a constant. $d\psi_3/dI = 0$ when the measurement is proceeded under a certain magnetic field. The inductance contributed by the MRF core can be written as:

$$L_2 = d\psi_2/dI = dM(H) \times NS/dI = NS\frac{dM(H)}{dI} \tag{2}$$

N and *S* are the number of the windings and the area of the coil, *M(H)* is the magnetic moment of the MRF core under the magnetic field *H*. According to the Faraday law of electromagnetic induction, the extra magnetic field *B* induced by the current applied to the coil could be expressed as:

$$\mathrm{BNS} = L_1 I \Rightarrow B = L_1 I/NS \tag{3}$$

So by combining Eq. (3) with Eq. (2), we get that:

$$L_2 = L_1\frac{dM(H)}{dB} = L_1 M'(H) \tag{4}$$

The inductance of the system has a linear relationship with the derivative of the magnetic moment of MRF, thus we could deduce the *M–H* relationship of the MRF which is the magnetic core in our coil system from the integration of *L* according to the combination of Eqs. (1) and (4):

$$M(H) = \int_0^H \frac{L - L_1}{L_1} dH \tag{5}$$

Eq. (5) is the theoretical expression of the dependence of the MRF magnetic moment on the magnetic field, which would support us to obtain the *M–H* curves of MRF experimentally by measuring the inductance of the coil system with the MRF being the magnetic core. Similarly, any other liquid magnetic materials and bulk magnetic materials are also appropriate to be measured for the magnetization property by this inductance-based method.

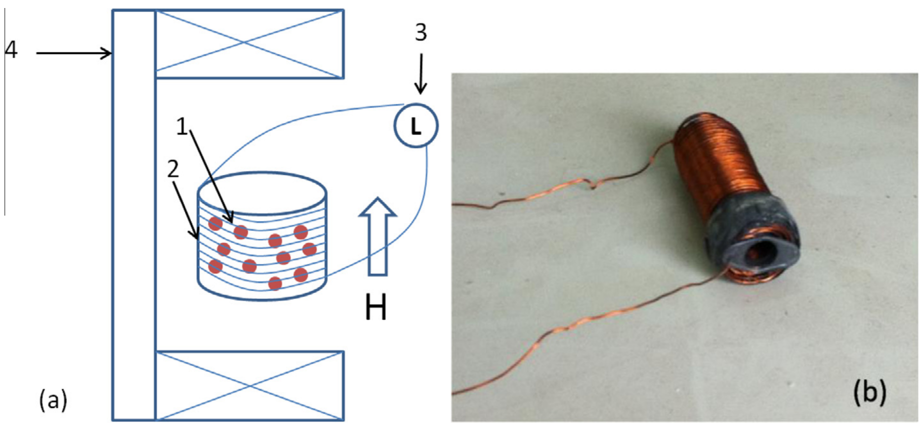

Fig. 1. (a) Schematic of the measurement system. (1) The MRF injected into the coil container. (2) The coil container encircled by the wires. (3) The digital inductance meter. (4) The electromagnet. The magnetic field was applied parallel to the axial direction of the coil. (b) Picture of the coil container. The length, the number of windings and the area of the container is 32 mm, 80 and 28 mm^2 respectively.