# Magnetic Characteristics of Magneto-rheological Fluid Materials with 2D Fluxes

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***Abstract*--This paper systematically reports our recent study on the magnetic properties of magneto-rheological (MR) materials under different patterns of flux density with two-dimensional (2D) magnetic excitations by using a single sheet tester. The principle of measurement, test system and calculation of power loss are presented. The experimental results, such as B-H vector loci and rotational power loss of MR materials, are analyzed and discussed. The results will be useful in the design and performance analysis of control system and smart structure using the MR materials.**

***Index Terms*—Magneto-rheological (MR) fluid material, single sheet tester (SST), two-dimensional (2D) measurement, magnetic characteristic.**

## I. Introduction

Magnetorheological (MR) fluid is one kind of controllable fluid, or field responsive fluid, in the family of smart materials. These fluids are different from the conventional smart materials. They are soft or semi-solid materials (typically dispersions or gels) rather than solids and liquids. MR materials have greatly captured the attention of researchers since the last decade due to their unique behaviors. Under the influence of an applied magnetic field, these remarkable materials can reversibly change their states within milliseconds between free-flowing, linear viscous liquids and semisolids having controllable yield strength. This promising feature makes MR materials smart, simple, quiet and capable of a rapid interface between an electronic control system and a mechanical system. MR materials have been widely used in various devices as "smart" materials [1-10].

Because of the lack of deep understanding of the magnetorheological characteristics and mechanism, the application of MR materials in engineering so far is still limited to dashpot-type dampers [5-6]. Only in recent years research work is carried out on the property characterization of the MR materials, followed by laboratory experiments and applications in devices [7-8]. In order to understand the inherent behavior, such as the hysteretic characteristics of the materials and associated devices, a great deal of research effort has been made by various researchers and some models are proposed.

However, these models fail to explain the magnetorheological mechanism in generating the device forces [9-10]. The effects of dynamic behavior and non-linear and vector characteristics of MR materials should be considered. It is very important to investigate and measure the general magnetic properties, deeply understand the magnetorheological mechanism, and establish mathematical models involving the magnetic hysteretic behavior and vector magnetization.

This paper systematically reports our recent study on the magnetic properties of an MR material under different patterns of flux density with two-dimensional (2D) magnetic excitations, using a single sheet tester (SST), which was designed and fabricated by the authors [11-12]. The principle of measurement, testing system and calculation of power loss are presented. Experimental results, such as the B-H hysteresis loop, **B**-**H** vector loci, and rotational power loss of the MR material are analyzed and discussed. The results can be helpful for the design and performance analysis of the control system and smart structure using MR materials.

## II. Technical Preparation

To achieve the objectives of the project as stated above, the measuring and experimental equipment, a modified single sheet tester (SST) - 2D tester which was built at the Center for Electrical Machines and Power Electronics (CEMPE), UTS, is used to investigate the magnetic characteristics of MR fluids. Fig. 1 illustrates schematically the whole testing system and the tested MR sample.

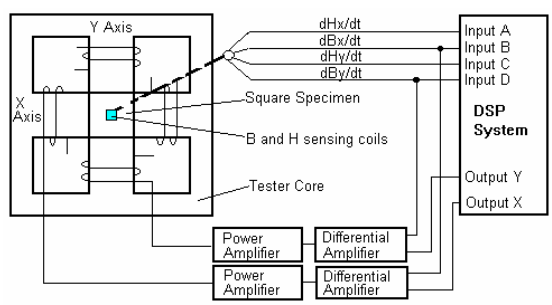


Fig. 1. Schematic illustration of a single sheet testing system

The 2D magnetic field in the sample is generated by two groups of excitation coils arranged on the X and Y axes, respectively. The excitation voltages and currents are supplied by two identical power amplifiers. By controlling the waveforms, magnitudes and phase angles of the excitation currents on the X and Y axes, any combination of one or two dimensional magnetic flux density vectors can be generated, such as an alternating magnetic flux density inclined at a specified angle from the X or Y axis, a purely circular or elliptical rotating magnetic flux density, or a rotating magnetic flux density of any specified locus. For the feedback control of the magnetic flux density components on the X and Y axes, two specially designed differential amplifiers with low and high pass filters are used. A PC based digital signal processing (DSP) system, AMLAB, is used for both function generation and data acquisition. It is also used for the calculation of the vectors **B** and **H** and the power losses under alternating or rotational exciting fields.

To determine the total core loss and **B**-**H** relationship in the sample, the flux density inside the sample and the field strength on the surface should be measured accurately. In this testing, 2D Sandwich H-coil is employed for the measurement of the surface field strength. The coils are installed very close to the sample surface to pick up the correct value of the surface field strength.

The surface field strength component on one axis can be calculated from the output voltage of the coil which is aligned with that axis by

$$H = \frac{1}{\mu_o K_H \int V_H dt} \tag{1}$$

where $V_H$ is the output voltage of the coil, and $K_H$ the coil coefficient, which is determined by calibration.

In the measurement, the 2D Sandwich H-coils were calibrated in a solenoid. The solenoid was excited with a sinusoidal voltage. The flux density in the center of the solenoid was calculated from the magnitude of the excitation current and double checked by a high precision Gauss meter. The sensing unit of two coils to be calibrated is mounted on a small turn-around table. When the output voltage signal of a coil, which is proportional to the excitation frequency and the flux density in the center of the solenoid, reaches the maximum, the axis of this coil is aligned with the solenoid axis. The coil coefficient was finally determined by averaging the results of a number of measurements. Here, $K_{Hx}$ = 0.006301, and $K_{Hy}$ = 0.005282.

B-coils are used for the measurement of the flux density because of their high accuracy. The flux density on one axis can be calculated by

$$B = \frac{1}{N_B A_B} \int V_B dt \tag{2}$$

$N_B$ is the number of turns, $A_B$ the cross sectional area, and $V_B$ the induced terminal voltage of the B-coil on the axis.

To manufacture the 2D B-coil, 0.05 mm enameled copper wire was employed. Two B-coils that are perpendicular to each other were wounded around a 15×15×0.96 mm block material, which can be dissolved in water. The block then was put in a glass frame and glued inside the closure, as shown in Fig. 2.

For measuring the rotational core loss, the field-metric method was employed, featuring high accuracy and great versatility. Moreover, the measured instantaneous **H** and **B** values can yield additional information, such as various loss contributions, the loci of **H** and **B** vectors, and harmonics, etc. By the Poynting's theorem, the total core loss $P_t$ in the sample can be calculated by

$$\begin{aligned} P_t &= \frac{1}{T\rho_m}\int_0^T \mathbf{H} \bullet \frac{d\mathbf{B}}{dt} dt \\ &= \frac{1}{T\rho_m}\int_0^T (H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt}) dt \end{aligned} \tag{3}$$

where $T$ is the time period of magnetization, $\rho_m$ the sample mass density, and $H_x$, $H_y$, $B_x$ and $B_y$ are the X and Y components of **H** and **B**, respectively.

## III. Measurement of MR Fluid

### A. *Formation of Square Specimen*

To obtain a homogeneous flux density distribution in the sample, the tester employs a square sheet specimen and the magnetic pole of tester is flat. A square module fabric glass is designed and manufactured by the authors as shown in Fig. 2. There is a 50×50×1 mm gap inside the glass. Filled with the MR fluid in the gap, a 1 mm thickness square specimen is formed.

The 50×50×1 mm sample of MR fluid material, which was provided by Lord Corporation, was systematically tested under various alternating flux densities and circular flux densities at the frequencies of 5 Hz and 10 Hz.

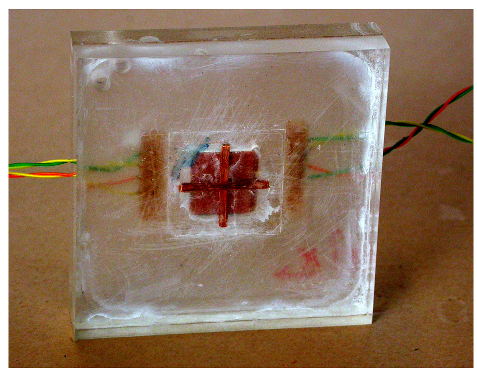

Fig. 2. A frame with 2D H and B coils and sample

### B. *B-H Loop & Loss under Alternating Field*

Fig. 3 illustrates the B-H loops of MR fluid material with 10 Hz sinusoidal excitations on the X axis, while Fig. 4 shows the power loss.

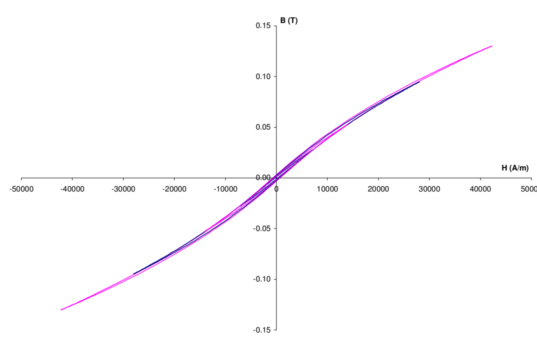


Fig. 3. B-H loops with 10 Hz alternating excitations on the X axis

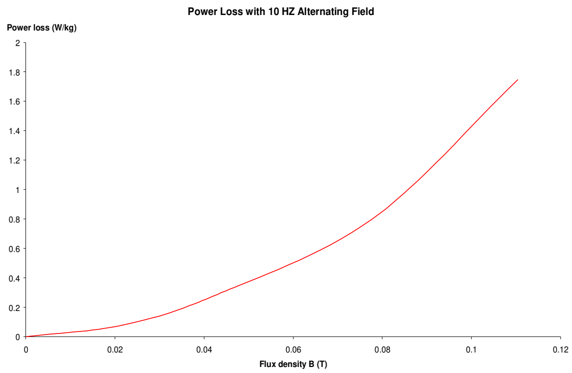


Fig. 4. Power loss with 10 Hz alternating field on the X axis

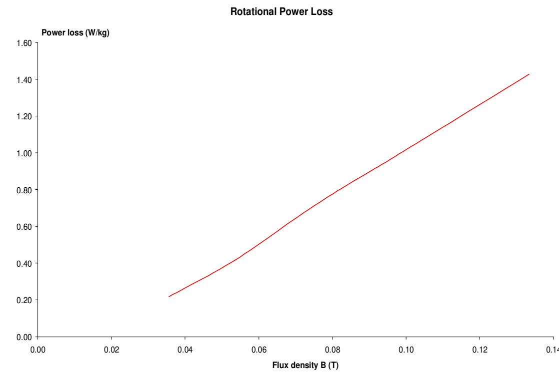


Fig. 6. Rotational power loss at different levels of **B**.

### *C. B & H Loci and Core Loss with Circular Flux*

Fig. 5 plots the **B** and **H** vector loci in the sample with rotating fields of 5 Hz. Fig. 5(a) illustrates the circular flux density vectors, which are controlled by the SST system, and Fig. 5(b) is the rotating field strength corresponding to the circular **B.**

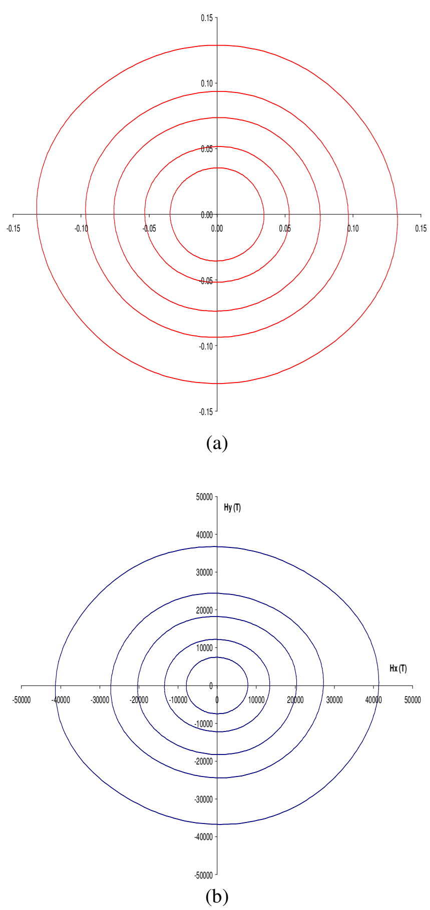


Fig. 5. Loci of (a) **B** and (b) **H** under circular flux density at 5 Hz.

Fig. 6 plots the total rotational power loss of MR fluid with different circularly rotating flux densities at 5 Hz magnetic field excitation.

### *D. Angular Relationship of B and H*

Fig. 7 shows the average angular relationship between **B** and **H** under the circular rotating excitations. Here, the flux density **B** lags the magnetic field strength **H**. It can be seen that the angles between **B** and **H** become smaller with the increase of magnetic field strength. This seems reasonable.

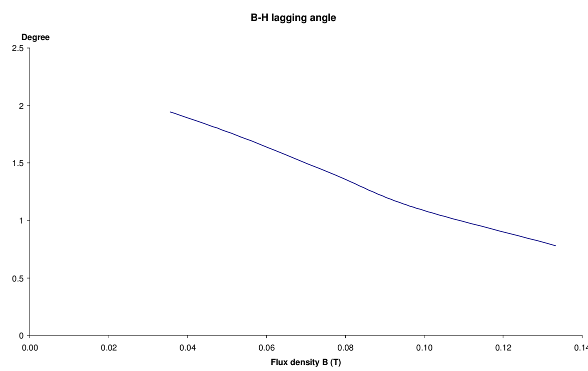


Fig. 7. Angle between **B** and **H** under rotating field.

### *E. Discussion*

The magnetic particles of MR fluid material suspend in the oil, and move or rotate with the magnetic field strength. The orientations of magnetic field strength **H** and magnetization **M** or flux density **B** were considered in the same direction before. It is probably correct under the circumstance of one dimension field excitation, but it is questionable under rotating field condition.

The angular relationship of **B** and **H** may be important in modeling the characteristics of MR material, particularly in investigating the complex dynamic relation between rheology and rotating flux excitations.

It can also be seen from Figs. 4 and 5 that the measurement of MR fluid has not reached the saturation level, because the permeability of MR fluid is very low, and the power amplifier for the field strength excitation is limited to 3 KW. An improved testing system has been proposed and the further investigation of MR fluid materials will be carried out.

## IV. Conclusions

In this paper, the magnetic characteristics of an MR fluid material is investigated with alternating and 2D rotating magnetic field excitations by using a single sheet tester. The B-H loops and **B**-**H** loci, which relate the dynamic and vector characteristics of MR fluid, are measured, analyzed and illustrated. A further test at the saturated level of MR material will be carried out.

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