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Magnetic induction measurements and identification of the permeability of Magneto-Rheological Elastomers using finite element simulations

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A R T I C L E I N F O

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A B S T R A C T

The isotropic and anisotropic magnetic permeability of Magneto-Rheological Elastomers (MREs) is identified using a simple inverse modelling approach. This involves measuring the magnetic flux density and attractive force occurring between magnets, when MRE specimens are placed in between the magnets. Tests were conducted using isotropic MREs with 10–40% and for anisotropic MREs with 10–30%, particle volume concentration. Magnetic permeabilities were then identified through inverse modelling, by simulating the system using commercially available multi-physics finite element software. As expected, the effective permeability of isotropic MREs was found to be scalar-valued; increasing with increasing particle volume concentration (from about 1.6 at 10% to 3.7 at 30% particle volume concentration). The magnetic permeability of transversely isotropic MRE was itself found to be transversely isotropic, with permeabilities in the direction of particle chain alignment from 1.6 at 10% to 4.45 at 30%, which is up to 1.07–1.25 times higher than in the transverse directions. Results of this investigation are demonstrated to show good agreement with those reported in the literature.

1. Introduction

Magneto-Rheological Elastomers (MREs) belong to a class of smart materials that can change their properties reversibly and almost instantaneously by the application of an external magnetic field. Not only mechanical properties such as stiffness, natural frequency and damping coefficient can be altered, but also the shape and electrical properties of MREs can change. This behaviour is caused by the magnetic interaction of the particles within the matrix material. MREs are promising materials that can potentially be used for a wide range of applications. Experimental analysis and constitutive models are required to predict the complex material behaviour of MREs, and therefore advance the development of applications using MREs. A necessary step in developing accurate constitutive models is a thorough understanding of the magnetic permeability of both isotropic and anisotropic MREs. This requirement provides the motivation behind the current investigation. MREs are particle-reinforced composite materials made of an elastomer as the matrix and usually iron particles as the magnetic component. The magnetisable particles are dispersed in the matrix material, and are locked in position after the elastomeric material is cured. Both isotropic and anisotropic materials can be prepared. The latter can be manufactured by exposing the uncured composite mixture to a magnetic field during the curing process. This aligns the particles into chains, resulting in both mechanical and magnetic anisotropy. Importantly, the magnetic permeability of anisotropic MREs is no longer a scalar quantity but is more accurately characterised as a tensor property.

So far, MREs have mainly been investigated under small strains; the change of storage modulus and the shift of natural frequency being of particular interest [1–3]. MREs are also known to be magnetostrictive materials [4,5]. From 2009 interest in the magnetic and electrical properties of MREs increased as their potential as sensing materials became recognised [6]. Their electrical resistance was found to increase with increasing magnetic field and increasing compressive force [7–9]. Magnetisation curves of MREs were studied by Boczkowska and Awietjan [10] and the magnetic permeability of anisotropic MREs was investigated by Zeng et al. [11].

In order to develop constitutive models able to predict the behaviour of MREs undergoing large strains, extensive experimental data derived from uniaxial and multi-axial deformation modes are required [12]. Ultimately, the magnetic permeability of MRE materials must also be included in constitutive models if their magnetorheological behaviour is to be fully and accurately predicted. To this end, the focus of the current paper is to

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characterise the magnetic permeability of MREs. This was done by measuring the magnetic field with a common Gaussmeter and simulating the magnetic field distribution using a finite element simulation.

Various techniques can be used to measure the magnetic permeability of materials, common methods include the *Faraday's* and *Guoy's* scale, which involve measuring force changes due to applied magnetic fields. A modified force balance method was employed by Vicente et al. [13] to measure the magnetic permeability of carbonyl iron powders in suspensions while Nimr et al. [14] measured the mass susceptibility of nanostructured and bulk *LiNiZ*-ferrite samples with a magnetic susceptibility meter and a resonance circuit [15]. *Vibrating sample magnetometry* measures the magnetic induction of an oscillating magnetised sample [16]. The technique was used by Göktürk et al. [17] on a thermoplastic elastomer incorporating ferromagnetic powders and by Bellucci et al. [18] on nickel-zinc ferrites formed by natural rubber. Anisotropic permeability can be measured by extending the method to include torque measurements on the sample; specialised equipment is commercially available to conduct such measurements. However, to the best of the author's knowledge, Zeng et al. [11] presented the first and until now, the only investigation into the magnetic permeability of anisotropic MREs. The magnetic properties of MREs were measured under 1D alternating and 2D rotating magnetic induction excitations, using a single sheet tester. The results of their investigation are included in Fig. 1 and show a large discrepancy with theoretical predictions. Another method is SQUID (Superconducting Quantum Interference Device) magnetometers, they provide a very sensitive way to measure the magnetic properties [19]. Favennec [20] demonstrated the use of inverse modelling using finite element analysis for identification of material properties. Their method required a preliminary sensitivity analysis to determine suitable measurement locations (of temperature in their investigation), before parameter identification via minimisation of an objective function.

The method introduced in this investigation is motivated in part by the constraints imposed by equipment availability but also by the desire to explore novel ideas to measure anisotropic permeability using an inverse finite element modelling strategy. As such, the aims of this investigation are two-fold; the primary objective is to characterise the anisotropic permeability of MREs, while a secondary objective is to examine the viability of using inverse finite element modelling in characterising the anisotropic magnetic permeability of composite materials. Inverse analysis of

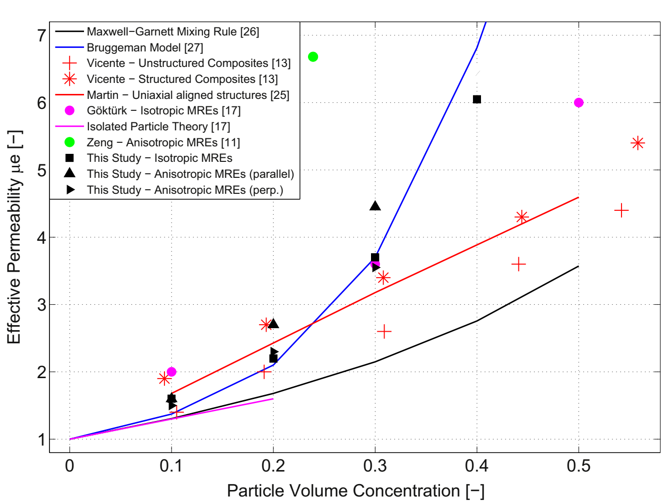

Fig. 1. Effective magnetic permeability, μ_e, versus the volume particle concentration. Theoretical and experimental investigations to determine the magnetic permeability of isotropic and anisotropic composites are compared.

electromagnet fields is already extensively used in imaging subsurface structures in for example, geophysics [21,22], or non-destructive testing [23] and also in identification of material parameters [20]. To the best of the author's knowledge, this is the first time that this technique has been attempted in relation to MREs. A retrospective critical assessment of the advantages and disadvantages of the method is provided in the conclusions section.

The structure of the remainder of the paper is as follows. An overview of theoretical predictions and measurements of the permeability of composites is provided in Section 2. The MRE material and the manufacture process used to prepare this material are described in Section 3. The experimental setup and measurements of both the magnetic field strength and the magnetic attractive force are reported in Section 4. In Section 5, finite element simulations using the commercial multi-physics software, Comsol are reported. The purpose of these simulations was to identify the magnetic permeability of MRE samples. The results are summarised and conclusions are presented in Section 6.

2. Review of the magnetic permeability of composites

To understand the finite element simulation and the identification process carried out (described in Section 5), a brief overview of electromagnetic theory is provided, common methods to measure the magnetic permeability, and prior investigation on the permeability of composites reported in the literature are summarised.

The relation between magnetic induction, **B**, and the magnetic field, **H** in vacuum, in air, or any other non-magnetic environment is constant and defined as

$$\mathbf{B} = \mu_0 \cdot \mathbf{H} \tag{1}$$

where μ_0 is the constant of permeability of a vacuum and has a value of $4\pi \cdot 10^{-7}$ Vs/Am or $1.256 \cdot 10^{-6}$ Vs/Am. The units of **H** are *ampere per meter*, and those of the magnetic induction, **B**, are *Teslas* (*SI* system of units). In a magnetic environment the value of **B** changes and is defined as

$$\mathbf{B} = \mu_0 \boldsymbol{\mu}_r \mathbf{H} \tag{2}$$

where the relative permeability, $\boldsymbol{\mu}_r = \boldsymbol{\mu}/\mu_0$. The permeability $\boldsymbol{\mu}_r$ is unity for a vacuum but can reach values above 1000 for soft magnetic materials such as iron [24]. For magnetically non-linear, ferromagnetic materials such as iron, the permeability, $\boldsymbol{\mu}$, is a function of **H**, and the magnetisation curve, **B**(**H**), is characterised by the initial permeability, $\boldsymbol{\mu}_{in}$, and by the saturation magnetisation, $\mathbf{B}_S$. The permeability of composites (such as MREs) is best described by an effective permeability, $\boldsymbol{\mu}_e$, which is predicted to be far smaller than that of iron [25]. In this work, MREs are assumed to behave magnetically linear with a constant permeability, $\boldsymbol{\mu}_e$, rather than one which is dependant on the magnetic field. As only relatively small magnetic field strengths, **B**, below 0.6 T, were applied in this investigation, this is a reasonable assumption and simplifies all further considerations about the magnetic permeability.

In this investigation both isotropic and anisotropic magnetic permeabilities are considered. For isotropic MREs the permeability is equally defined in all directions with $\mu_{iso} = \mu_X = \mu_Y = \mu_Z$. For anisotropic MREs with the particle alignment in the *Z*-direction the permeability parallel to the particle alignment is defined with $\mu_{\parallel} = \mu_Z$ and perpendicular to the alignment direction with $\mu_{\perp} = \mu_X = \mu_Y$, analogue for anisotropic MREs with particle alignment in the *X*-direction $\mu_{\parallel} = \mu_X$ and $\mu_{\perp} = \mu_Y = \mu_Z$, and for the anisotropic MREs with alignment in the *Y*-direction $\mu_{\parallel} = \mu_Y$ and $\mu_{\perp} = \mu_X = \mu_Z$. Because $\boldsymbol{\mu}$ is anisotropic it can be denoted as