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Research articles

Linear magneto-viscoelastic model based on magnetic permeability components for anisotropic magnetorheological elastomers

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ABSTRACT

A new magneto-viscoelastic model is presented for anisotropic magnetorheological elastomers (MREs), which combines the dynamic behaviour and magnetic permeability components. Five samples were synthesised with different particle contents. Dynamic properties were measured using a rheometer equipped with a magnetorheological cell. A four-parameter fractional derivative model was used to describe MRE viscoelasticity in the absence of a magnetic field. The magnetic permeability of each sample was measured with a vibrating sample magnetometer. From experimental measurements of longitudinal and transverse components of the magnetic permeability, the dependency with magnetic field was modelled. The new magneto-induced modulus model proposed in this work is based on the model developed by López-López et al. [19] for magnetorheological fluids, and was adapted for anisotropic MREs. The proposed model includes the longitudinal and transverse components of magnetic permeability, and it is valid for the linear viscoelastic region of anisotropic MREs. The errors between experimental values and the values predicted by the model do not exceed 10%. Hence, a new linear magneto-viscoelastic model for anisotropic MREs is developed, which predicts the effect of magnetic field on the dynamic shear modulus as a function of magnetic field intensity and frequency.

1. Introduction

Magnetorheological elastomers (MRE) consist of ferromagnetic particles embedded in an elastomeric matrix [1]. When an external magnetic field is applied to these materials, their mechanical properties are modified; and they are referred to as smart materials.

The properties of MREs are completely dependent on the particle distribution, which is therefore considered an important characteristic of MREs. Isotropic MRE samples are prepared by vulcanisation without an external magnetic field; these samples have a random particle distribution [2,3]. However, if an external magnetic field is applied during the vulcanisation process, the particles are aligned in the direction of the magnetic field, and consequently, particle chains or thicker chain aggregates are obtained; these samples are called anisotropic MREs [4,5].

Dynamic properties of anisotropic MREs are dependent on the matrix, particle content, and magnetic field. The predominant behaviour is the viscoelasticity, owing to the nature of the main component of these materials: silicone rubber or natural rubber [6,7]. This behaviour has been modelled for MRE materials by combining different elements such as dashpots and springs in different configurations [8,9]. To obtain a better fit to experimental data, more elements have been introduced by increasing the number of fitting parameters [10].

The fractional derivative model can be used to decrease the number of material parameters, and these parameters have a physical significance [11]. By using these advantages, the viscoelastic behaviour of isotropic [7,12] and anisotropic [13,14] MREs have recently been modelled using fractional derivative models. Agirre-Olabide et al. [12] used four material parameters to simulate the viscoelastic behaviour of isotropic MREs, and Xu et al. [7] combined a fractional Kelvin and Maxwell model in the parallel configuration to develop a higher order model (seven material parameters). Guo et al. [13] combined an Abel dashpot (fractional derivative element) and a spring in a series configuration, while Zhu et al. [14] employed a parallel configuration. Hence, three material parameters were used to predict the viscoelastic behaviour of anisotropic MREs.

The effect of the magnetic field on the properties of anisotropic MREs has been widely studied. Many models have assumed that perfectly aligned chains are created during the vulcanisation process. Jolly et al. [15,16] analysed the interaction of two particles by using dipole–dipole moments, while Davis [17] and Shen

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et al. [18] studied the interaction of each particle in the whole chain of particles. Bica et al. [4] used a dipolar magnetic moment approach and the ideal elastic body model.

López-López et al. [19] proposed a model for magnetorheological fluids by introducing the influence of aggregates having a body centered tetragonal (bct) internal structure (a more stable and more realistic structure), and they combined numerical simulations of the composite magnetic permeability with the analytical model predicting the stress–strain relationship. For MREs, Leng et al. [20] proposed an effective permeability model to estimate the shear storage modulus, and Dong et al. [21] developed a theoretical model for chains composed of magnetic particles and normal pressure, based on the effective permeability calculated by the Maxwell–Garnett mixing rule. Chen et al. [22] proposed a finite-column model to simulate the field-induced shear modulus.

The magnetic permeability of materials can be measured by using different techniques. De Vicente et al. [23] used a modified force balance method to measure the magnetic permeability of carbonyl iron powder suspension. Bellucci et al. [24] used vibrating sample magnetometry on a magnetic nanocomposite based on natural rubber. Schubert and Harrison [25] identified the permeability of isotropic and anisotropic MREs using an inverse modelling approach. Furthermore, they calculated the permeabilities of anisotropic MREs in the particle alignment direction and perpendicular to the alignment direction. However, de Vicente et al. [23] measured the permeability of carbonyl iron powder in a suspension and showed that the permeability decreases with the internal magnetic field.

A few magneto-viscoelastic models have been developed by coupling viscoelastic and magnetic interaction models. A classical four parameter magneto-viscoelastic model has been proposed by Li et al. [26], and all material parameters were fitted to experimental data for each magnetic field density. The magneto-viscoelastic behaviour using fractional derivatives has been modelled for isotropic [27] and anisotropic [13,14] MREs. Agirre-Olabide et al. [27] proposed a three-dimensional magneto-viscoelastic model within the linear viscoelastic region for isotropic MREs, by coupling a fractional-derivative-based viscoelastic model with a magnetic-field-dependant model. Conversely, the magneto-viscoelastic model proposed in [13,14] for anisotropic MREs is composed of a serial configuration a fractional derivative Maxwell model and a spring, which is dependent on the magnetic field and is modelled assuming chain-like structures. The strain amplitudes applied were 0.1% in [13] and 25% in [14], and the maximum magnetic field intensity was 300 mT.

In this work, we developed a new linear magneto-viscoelastic model for anisotropic MREs based on the longitudinal and transverse components of magnetic permeability. We modified the model developed by López-López et al. [19] for magnetorheological fluids, and we adapted it for anisotropic MREs. The new model assumes bulk column-like aggregates in the MR samples, and coupled it with the viscoelastic model. The viscoelastic model is based in a four-parameter fractional derivative model. We studied the influence of the magnetic field on the longitudinal and transverse components of the magnetic permeability of anisotropic MREs. We proposed a model to predict the evolution of the permeability components as a function of the external magnetic field (100–360 kA/m) and extend it for higher magnetic fields. The proposed new linear magneto-viscoelastic model was validated with experimental data, and can be extended to larger magnetic field and frequency conditions.

2. Experimental

In this work, anisotropic magnetorheological elastomers were synthesised using a room-temperature-vulcanising silicone rubber and soft magnetic particles; five particle contents were analysed. Two different characterisation techniques were performed; the dynamic behaviour was measured using a rheometer equipped with a magnetorheological device, and the magnetic properties were measured using a vibrating sample magnetometer (VSM).

2.1. Preparation of anisotropic samples

In this study, we used two components based on room-temperature-vulcanising vulcanised silicone rubber (RTV-SR): the main matrix WACKER Elastosil® M 4644A and the vulcaniser WACKER Elastosil® M 4644B mixed in a 10:1 ratio. The embedded soft magnetic spherical particles were carbonyl iron particles HS (BASF The Chemical Company, Germany) with a particle size of 1.25 ± 0.55 μm. Samples of five different particle volume fractions were prepared: 0%, 5%, 10%, 15%, and 20%.

The main matrix (Elastosil® M 4644A) and particles were mixed at the mentioned contents, and when a homogeneous mixture was obtained, the vulcaniser (Elastosil® M 4644B) was added. Every time a component was added, vacuum cycles for 30 min were applied to remove air bubbles generated during the mixing. Finally, the homogenous mixture was poured into a 1-mm-thick mould.

During the vulcanisation process, a magnetic field was applied in the thickness direction to obtain a chain alignment of the particles in the direction perpendicular to the shear strain applied during the rheometric experiments (Fig. 1). A magnetic field of a flux density of 130 mT was applied using a pair of permanent magnets placed on the both sides of the mould.

A Nova Nano SEM 450 scanning electron microscope (SEM) was used to observe the particle alignment and distribution (Fig. 2). The images were taken in a low vacuum condition with an acceleration voltage of 18 kV.

2.2. Magnetorheology

The dynamic properties of anisotropic MRE were measured using an Anton Paar Physica MCR 501 rheometer equipped with a MRD 70/1T magnetorheological cell, and a parallel plate configuration was used. To avoid slipping between the sample and plates, one of the plates had a serrated surface (PP20/MRD/TI/P2); a normal compressive force of 5 N was applied to the sample in order to increase the contact of the sample to the rheometer plates [28]. The sample's diameter and thickness were 20 mm and 1 mm, respectively. To check the reproducibility, three samples were studied for each particle content.

The samples were subjected to torsional deformation generated by a periodic oscillatory rotation of the upper rheometer plate. A strain amplitude of 0.01% was used in the frequency sweep tests to guarantee that all tests were performed in the linear viscoelastic

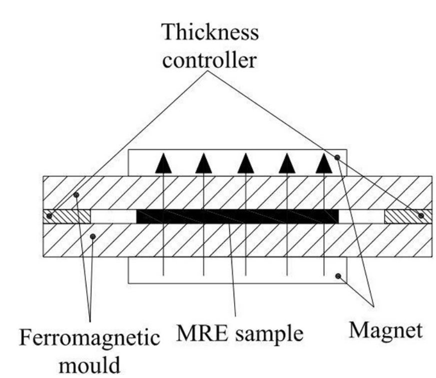

Fig. 1. Sketch of the anisotropic MRE sample vulcanisation device.