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A general result for the magnetoelastic response of isotropic suspensions of iron and ferrofluid particles in rubber, with applications to spherical and cylindrical specimens

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Abstract

This paper puts forth an approximate solution for the effective free-energy function describing the homogenized (or macroscopic) magnetoelastic response of magnetorheological elastomers comprised of non-Gaussian rubbers filled with isotropic suspensions of either iron or ferrofluid particles. The solution is general in that it applies to $N = 2$ and 3 space dimensions and any arbitrary (non-percolative) isotropic suspension of filler particles. By construction, it is exact in the limit of small deformations and moderate magnetic fields. For finite deformations and finite magnetic fields, its accuracy is demonstrated by means of direct comparisons with full-field simulations for two prominent cases: (*i*) isotropic suspensions of circular particles and (*ii*) isotropic suspensions of spherical particles.

With the combined objectives of demonstrating the possible benefits of using ferrofluid particles *in lieu* of the more conventional iron particles as fillers and gaining insight into recent experimental results, the proposed homogenization-based constitutive model is deployed to generate numerical solutions for boundary-value problems of both fundamental and practical significance: those consisting of magnetorheological elastomer specimens of spherical and cylindrical shape that are immersed in air and subjected to a remotely applied uniform magnetic field. It is found that magnetorheological elastomers filled with ferrofluid particles can exhibit magnetostrictive capabilities far superior to those of magnetorheological elastomers filled with iron particles. The results also reveal that the deformation and magnetic fields are highly heterogenous within the specimens and strongly dependent on the shape of these, specially for magnetorheological elastomers filled with iron particles. From an applications perspective, this evidence makes it plain that attempts at designing magnetrostrictive devices based on magnetorheological elastomers need to be approached, in general, as structural problems, and not simply as materials design problems.

Key words: magnetorheological elastomers, ferrofluid inclusions, magnetostriction, finite magnetoelastostatics

1. Introduction

Ostensibly due to the renewed experimental impetus started during the 1990s (see, e.g., Shiga et al. 1995; Jolly et al., 1996; Ginder et al., 1999), increasing efforts have been devoted by the mechanics community to construct continuum models capable of describing the magnetoelastic response of magnetorheological elastomers under finite deformations (involving arbitrary finite strains and rigid rotations) and finite magnetic fields. These efforts can be roughly classified into two categories: (*i*) top-down or phenomenological approaches in which macroscopic free energies are postulated based on macroscopic experimental observations (see, e.g., Kankanala and Triantafyllidis, 2004; Dorfmann and Ogden, 2005; Bustamante et al., 2011; Danas

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