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Experimental nonlinear dynamics of a geometrically imperfect magneto-rheological elastomer sandwich beam

Tanju Yildirim [a], Mergen H. Ghayesh [a,*], Weihua Li [a], Gursel Alici [a,b]

[a] School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Northfields Avenue, NSW 2522, Australia

[b] ARC Centre of Excellence for Electromaterials Science, University of Wollongong, Innovation Campus, NSW 2522, Australia

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ABSTRACT

Experimental investigations were carried out on the nonlinear dynamic response of a clamped–clamped geometrically imperfect magneto-rheological elastomer (MRE) sandwich beam with a concentrated mass at the centre when loaded with a point excitation. Experiments have been conducted for: (i) a geometrically imperfect aluminium beam; (ii) a geometrically imperfect MRE sandwich beam in the absence of a magnetic field; (iii) a geometrically imperfect MRE sandwich beam in the presence of a magnetic field; (iv) a MRE sandwich beam with different geometric imperfection amplitudes. An electrodynamic shaker excited each system and the corresponding displacement of the concentrated mass was measured; an array of magnets has been used to investigate the effects of changing magnetic field strength on the nonlinear dynamic response of the geometrically imperfect MRE sandwich beam. It has been shown that the geometrically imperfect aluminium beam displays initial softening behaviour followed by strong hardening-type nonlinearity; with a MRE layer the motion characteristics of the geometrically imperfect sandwich beam no longer exhibits initial softening behaviour however, the MRE layer in the absence and presence of an external magnetic field all exhibit strong hardening-type nonlinearities—a significant qualitative change was observed in the nonlinear dynamical behaviour of the system.

1. Introduction

Magneto-rheological elastomers (MREs) [1–3] are a new class of smart materials which are gaining high interest due to a controllable shear modulus when an external magnetic field is applied [4–6]; MREs are a composite material where magnetic iron particles are suspended in a rubber matrix. Due to the controllable *stiffness* [7] and *damping* [8] properties of the MRE, this smart material has a wide variety of applications in many industries such as motion absorbers in civil structures [9–13], railway applications [14] and in automotive suspension [15,16]. The MREs controllable mechanical properties make it ideal in applications for reducing undesirable motion and hence reducing fatigue on structures and machine elements.

Geometrically imperfect beams are a high possibility to be produced during manufacturing or they can be developed over time by fatigue loading; geometrically imperfect beams have considerably different dynamical responses when compared to straight beams—the changing dynamic response of a geometrically imperfect beam has led to the investigation to analyse the effect of MRE on the *nonlinear* system dynamics. *Linear* theory is not capable of describing the motion characteristics of a system subject to fairly *large* displacements; a *nonlinear* investigation is required, as done in this paper.

MRE is used as the core element in straight sandwich beams to mitigate the linear resonance. Sun et al. [17] investigated the controllable capability of an adaptive MRE sandwich beam; the experimental investigations showed that the MRE damps unwanted motion. Nayak et al. [18] investigated the stability of a sandwich beam theoretically and it is shown that the stability of the sandwich beam can be changed with varying lengths and positioning of the MRE patch. Zhou and Wang [19,20] investigated the dynamic response of a MRE sandwich beam with different external magnetic fields; numerical simulations were conducted for the dynamic response of a MRE sandwich beam, for different loads including a vertical force distributed uniformly in a narrow region around the centre of the beam—it was shown that the anti-resonance frequencies change by 40%, however the resonant frequencies only exhibit a slight shift. Hu et al. [21] conducted an experimental study on the dynamical response of a sandwich beam containing two aluminium layers with a MRE core under non-homogeneous magnetic fields; it was shown that a reduction of 13.9% is achieved on the first mode of transverse motion. More recently, the semi-active control of a MRE

* Corresponding author.
E-mail address: mergen@uow.edu.au (M.H. Ghayesh).

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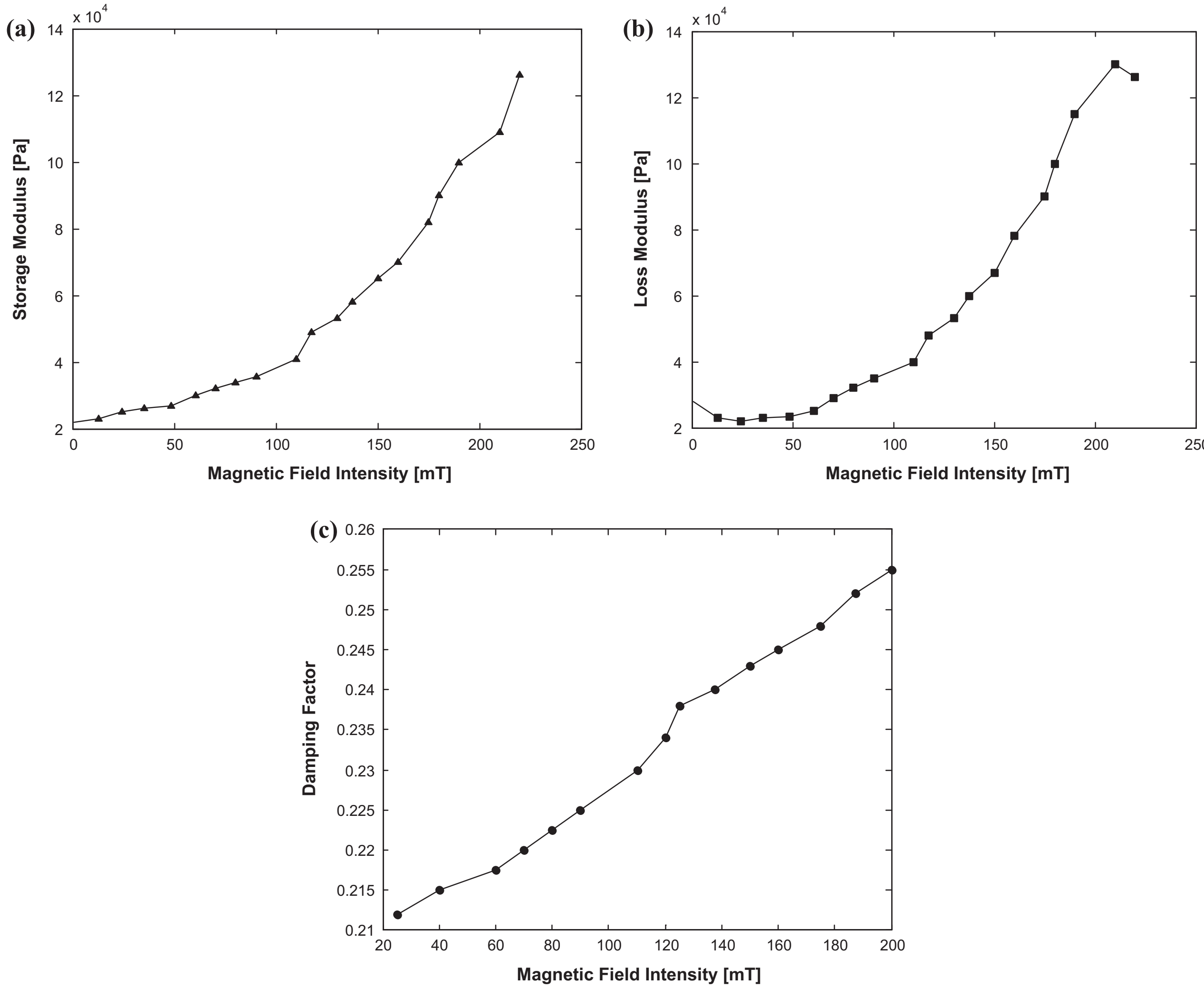

Fig. 1. Rheometer readings for MRE sample (a) storage modulus; (b) loss modulus; (c) damping factor.

sandwich beam was investigated under different loadings [22]; results showed the changing stiffness and damping of the MRE layer controls the motion amplitude.

To the authors' best knowledge, there are no previous studies that have *experimentally* investigated the *nonlinear dynamic response* of a *geometrically imperfect MRE sandwich beam*; this paper is the first to do so—specifically, this paper investigates the nonlinear dynamical behaviour of a bilayer MRE sandwich beam using MRE as one layer and aluminium as the other layer. Experiments have been conducted for the nonlinear dynamical response of a geometrically imperfect aluminium beam, a geometrically imperfect MRE sandwich beam with *different imperfection amplitudes*, in the *absence* and *presence* of an external magnetic field. The qualitative and quantitative modifications on the nonlinear system dynamics has been investigated and as we shall see slight changes in geometric imperfections and the presence of a magnetic field (changing the stiffness and damping of the MRE layer) have significant effects on the nonlinear motion characteristics.

2. MRE fabrication process and system description

This section describes the procedure for fabricating the MRE-layer; testing the mechanical properties of the smart material is also discussed. The problem of a geometrically imperfect beam and the experiments that were conducted to assess the *nonlinear motion characteristics* are also explained.

2.1. Fabrication and testing of the MRE

A MRE has been fabricated using 80% iron particles (Carbonyl iron, C_{3518}, Sigma–Aldrich Pty Ltd.) with 5 μm mean particle size, 10% silicone rubber (Selleys Pty. Ltd) and 10% silicone oil; a 0.1 mm layer of MRE has been bonded to a 0.5 mm aluminium beam and allowed to cure, creating a bilayer MRE sandwich beam (beam B). MREs are characterised by their inherent ability of changing modulus and damping, in the presence of an external magnetic field.

Fig. 1 shows the loss modulus, storage modulus and damping factor for the MRE composition 80% iron particles, 10% silicone rubber and 10% silicone oil; these properties were measured using a parallel plate rheometer (MCR 301, Anton Paar Companies, Germany) using a magnetic sweep. The storage modulus is a measure of the viscoelastic material to store energy and the loss modulus refers the materials ability to dissipate deformation energy into heat; as shown in Fig. 1(a)–(c), the MREs mechanical properties (storage modulus, loss modulus and damping factor) increase with an increasing external magnetic field.

2.2. System description

The problem presented in Fig. 2 is a clamped–clamped geometrically imperfect sandwich beam with a concentrated mass at the centre of the beam, where *m* is the mass at the centre of the beam