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Numerical modeling of Galfenol magnetostrictive response

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ABSTRACT

Specimens of magnetostrictive materials can transform a variation of their stress-induced size into a variation of a produced magnetic field and vice versa. These phenomena are utilized in magnetostrictive energy harvesters, vibration sensors, etc. Mathematical models of magnetostrictive materials vary from complex hysteretic models to relatively simple non-hysteretic models. In this paper, three mathematical models of Galfenol are considered, namely a non-hysteretic model, a non-hysteretic model with a feedback loop, and a model where the hysteresis is represented by the Preisach operator with a simplified Preisach density function. The parameters of these models are identified from measured magnetic and magneto-elastic curves. All the models are applicable in technical praxis. The output of the non-hysteretic model with a feedback loop best fits the measured data and, to some extent, reproduces fine features of magneto-elastic curves.

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1. Introduction

Sophisticated mathematical modeling of the materials with memory is based on the use of hysteresis operators. Although their origins can be traced back to the end of the first third of the 20th century, see [1], a relevant more advanced analysis has only been developed in the last three decades, see [2–7]. The behavior of materials with memory depends on the loading history. These materials are the subject of research and modeling in various fields, including magnetism [8,9], piezoelectricity [10,11], nonlinear elasticity [12,13], moisture transport [14], etc. Magnetostrictive materials form a subclass of materials with memory that is characterized by the interplay between mechanical stress and magnetic field.

Magnetostrictive materials have found applications, for example, in vibration sensors and energy harvesting devices, see [15–20], for instance.

Attention is paid to the mathematical modeling of problems involving hysteresis. Among other topics, the author of [21] deals with the finite element approximation of parabolic equations with hysteresis. Dissertation [22] deals with elasto-plastic waves in 1D and presents relevant numerical methods as well as their analysis. A finite element approach to the interactions of elastic, electric, and magnetic effects in ferromagnetic materials is shown in [23].

Various mathematical models of magnetostriction have been proposed and can be found in the literature, see, for instance, [24], where a family of models is briefly introduced; another approach is presented in [25].

In energy harvesting, Galfenol (iron–gallium alloy) is an attractive material [26,27]. To model its input–output behavior, several options are available. Among them, a hysteresis model based on the Preisach hysteresis operator is quite popular.

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However, a sufficiently accurate identification of the Preisach density function is not a trivial task though various techniques have been proposed, see [6,24,28–31], for instance.

In [24], the Preisach density function is identified from magnetic and magneto-elastic curves measured on a Galfenol specimen under a uniaxial compressive load. It is assumed that the density function belongs to a certain rather special set of functions. Based on this material model, a magnetostrictive energy generation is modeled and optimized in [17]. Also [16,20] follow this research; the latter paper with the emphasis on a circuit model representing the device.

The hysteresis model based on the Preisach density function from [17,24] is computationally demanding. Since the hysteresis effect in Galfenol is quite small, a simpler, hysteresis-free model is worth considering, see Section 2. It turns out, however, that although the model output is satisfactorily close to the measured magnetization data, its ability to reproduce the width of the measured magneto-elastic curves is less acceptable. Moreover, the model is unable to capture tooth-like bumps observed in the magneto-elastic curves at vanishing intensity of the magnetic field. To widen the model-generated magneto-elastic curves and to capture the magneto-elastic bumps, a feedback of the mean field interaction type is added to the non-hysteretic model in Section 3. That is, unlike Section 2, the response is dependent not only on the strength of the magnetic field and on the mechanical stress, but also on the current level of magnetization. Based on Section 2, another simplifying approach is considered in Section 4, where the Preisach density function [17,24] is replaced by a density function stemming from the non-hysteretic model and allowing for faster integration. Observations and conclusions are presented in Section 5.

2. Identification of a magnetostrictive material model without hysteresis

2.1. Model

Like in [24], where a hysteretic model is identified, we focus on the identification of non-hysteretic model parameters and on the comparison of the model response with the Galfenol experimental data that are identical with those used in [24]. The data consist of six pairs of measured magnetic and magneto-elastic curves that show the dependence of magnetization and strain on the strength of an applied magnetic field. To obtain six different pairs of curves, six levels of mechanical stress were applied to the Galfenol specimen, and the specimen response to the variation of magnetic field strength was measured. The experimental setup is described in [24]. Its arrangement allows for the characterization of the magnetic field by a scalar quantity h, the strength of the field.

The effect of hysteresis is rather small in Galfenol, that is, the hysteresis loops are narrow. The low amount of hysteresis as well as the time-consuming hysteresis-related calculations led to considering a simplified model where hysteresis is neglected and included into measurement errors.

In this model and for a fixed stress σ, the magnetization m_σ and the strain ε_σ as functions of the magnetic field strength h are determined by a σ-independent function g of one variable and a value $\tilde{f}(\sigma)$ as follows

$$m_\sigma(h) = g\left(\frac{h}{\tilde{f}(\sigma)}\right), \tag{1}$$

$$\varepsilon_\sigma(h) = -\tilde{f}'(\sigma) G\left(\frac{h}{\tilde{f}(\sigma)}\right), \tag{2}$$

where $h \in \mathbb{R}$ (real numbers) and

$$G(u) = \int_0^u v g'(v)\,\mathrm{d}v \overset{\text{by parts}}{=} u g(u) - \int_0^u g(v)\,\mathrm{d}v; \tag{3}$$

the prime stands for the derivative with respect to the indicated variable, that is, σ or v. In (2), ε_σ is the inelastic part of the total strain, that is, $\varepsilon_\sigma = \varepsilon_{\text{total}} - \sigma/E$, where E is the Young modulus. It is assumed that g is a real continuous and continuously differentiable function on $\mathbb{R}$ and that g is an odd function. As a consequence, $g(0) = 0$. Our goal is to identify g and $\tilde{f}$.

On the basis of both the hysteresis nature and measurements, we can assume that a saturation value $v_{\text{sat}} > 0$ exists such that

$$\text{for each } v \text{ real and } |v| \ge v_{\text{sat}} \text{ the relation } g(v) = g(v_{\text{sat}}) \text{ is valid.} \tag{4}$$

Similarly, we can conclude from the measurements and (2)–(4) that the saturation occurs in the strain, too, that is,

$$\varepsilon_{\text{sat}}(\sigma) = \lim_{h\to+\infty} \varepsilon_\sigma(h). \tag{5}$$

By introducing

$$G^\infty = \lim_{u\to+\infty} G(u) \overset{(3),(4)}{=} G(v_{\text{sat}}) \tag{6}$$

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