

Modeling and Simulation of Mechanical Energy Harvesting Using the Feedback Preisach Model of Hysteresis

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Over the past few decades, energy harvesting has been a topic of interest. Recently, magnetoelastic materials have been utilized in a broad spectrum of applications including actuation, sensing, vibration damping and mechanical vibration energy harvesting. This paper aims to present an efficient simulation and modeling approach for electrical energy harvesting from mechanical vibrations. The proposed approach utilizes the scalar feedback Preisach-type model of hysteresis cascaded to a scaling polynomial block. Details of the proposed methodology, experimental testing and simulation results are given in the paper.

Index Terms—Computational modeling, energy harvesting, magnetic hysteresis, magnetoelasticity.

I. INTRODUCTION

OVER the past few decades, energy harvesting has been a topic of interest. As a result, research efforts covering a wide spectrum of energy harvesting techniques have been reported (refer to [1] and [2]). Recently, magnetoelastic materials, especially Terfenol and Galfenol, have been widely used in actuation, sensing, vibration damping and energy harvesting (see, for instance, [3]-[8]). The purpose of this paper is to present an efficient simulation and modeling approach for electrical energy harvesting from mechanical vibrations.

The proposed approach utilizes the scalar feedback Preisach-type model of hysteresis where the feedback term is mapped to the applied mechanical stress. In the suggested methodology, a scaling polynomial block is cascaded to the hysteresis model output as shown in Fig. 1 to fine tune the overall quantitative accuracy. In this figure, at a time instant t the magnetic field input, the model flux density output, the overall system flux density output and the mapped mechanical stress are denoted by $H(t)$, $B(t)$, $B_c(t)$, and $\sigma_s(t)$, respectively. It is worth mentioning that the sophistication resulting from dealing with a closed loop feedback control system having a history-dependent feed-forward block is significantly minimized using the perturbation approach presented in [9] and [10].

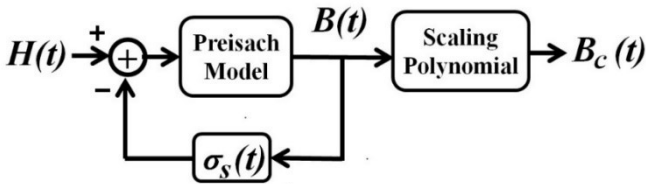


Fig. 1. Block diagram of the proposed energy harvesting methodology.

II. THE PROPOSED MODEL AND ITS SIMULATION RESULTS

It has been shown that the effect of a compressive stress on a magnetized magnetic rod may be modelled by the feedback Preisach hysteresis model where the applied stress is

represented by a negative feedback term [10]. Given the fact that the feedback term is treated as a perturbation of the feed-forward control block, it is important to employ a scaling transfer function that maps the maximum stress under consideration as a small ratio of the normalized maximum flux density output.

The proposed model may be given by the expressions:

$$B_c(H, \sigma) = \sum_{u=0}^{N_\sigma} \sum_{v=0}^{N_B} C_{u,v} [\sigma_s]^u [B]^v, \quad (1)$$

where, N_σ and N_B define the polynomial degrees, while $C_{u,v}$ represents the fitting polynomial coefficients, respectively.

For a specific instant t , B in (1) may be computed by expressions (2) and (3) for a monotonically increasing and decreasing applied magnetic field inputs, respectively.

$$B(t) = \frac{1}{\left(1 - \sigma_s(t) \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{-h_{n-1}, -H}\right)} \left[B(H(t)) + \sigma_s(t) \left\{ \sum_{j=1}^{n-1} \left(B(t)_j^+ \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_j, h_j} + B(t)_j^- \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_j, h_j} - B(t)_j^+ \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_j, h_{j-1}} - B(t)_j^- \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_j, h_{j-1}} \right) \right\} + B(t)_{n-1}^- \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{-h_{n-1}, H} + B(t)_{n-1}^- \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_n, h_{n-1}} \right], \quad (2)$$

$$B(t) = \frac{1}{\left(1 - \sigma_s(t) \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_n, H}\right)} \left[B(H(t)) + \sigma_s(t) \left\{ \sum_{j=1}^{n-1} \left(B(t)_j^+ \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_j, h_j} + B(t)_j^- \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_j, h_j} - B(t)_j^+ \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_j, h_{j-1}} - B(t)_j^- \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_j, h_{j-1}} + B(t)_j^+ \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_n, H} - B(t)_n^+ \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_n, h_{n-1}} - B(t)_{n-1}^- \frac{\partial B_{\alpha\beta}}{\partial \alpha} \Big|_{H_n, h_{n-1}} \right) \right\} \right]. \quad (3)$$

It should be pointed out that in the previous two expressions n represents the total number of applied field local maxima accumulated by the hysteresis model, $B_{\alpha\beta}$ is the flux density

value corresponding to the applied magnetic field value β along a first-order-reversal curve initiated from the applied magnetic field value α , $B(H)$ is the hysteresis model output corresponding to the applied magnetic field value H in the absence of any feedback terms, while B_j^+ and B_j^- are the feedback hysteresis model outputs corresponding to the j^{th} applied magnetic field local maximum H_j and local minimum h_j , respectively.

To test the proposed approach, normalized first-order-reversal B - H curves of a Terfenol-D rod, 2 cm long and having a square cross-section of 0.5 cm side length, at a minimal pre-stress value of 25 N were deduced from the major loop given in Fig. 1 in accordance with [11]. Throughout the simulations the mechanical stress, the flux density and the applied magnetic field were normalized according to:

$$\sigma_s = \frac{(\sigma - 25)}{5000}, B = \frac{B_{actual}}{1.0}, H = \frac{H_{applied}}{300000}. \quad (4)$$

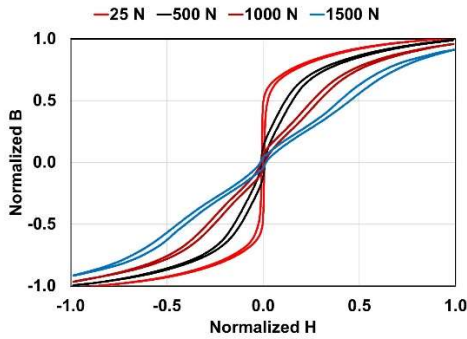


Fig. 2. Measured B - H curves of the Terfenol-D rod under consideration for different applied mechanical stress values.

Analogous simulations were carried out and using the least squares curve fitting technique for $N_\sigma = 3$ and $N_B = 3$ it was possible to obtain an overall good quantitative match for the measured curves as shown in Fig. 2. Values of C_{01} , C_{11} , C_{21} , C_{31} , C_{03} , C_{13} , C_{23} , and C_{33} that led to a good match were 1.078, -7.938, 26.626, -28.642, -0.1058, 8.620, -29.299, and 28.417, respectively.

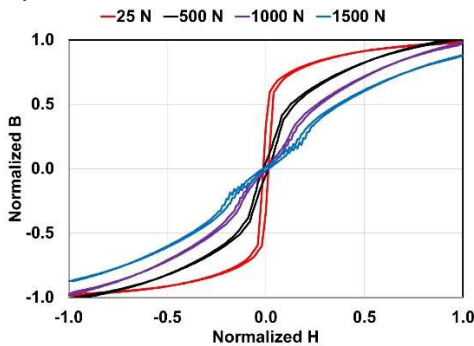


Fig. 2. Computed B - H curves corresponding to the measured Terfenol-D rod curves shown in Fig. 1.

The validity of the model for simulating energy harvesting was assessed by comparing measured and computed B variation as a result of varying the stress at a constant applied field. Sample result of this comparison is shown in Fig. 3 for a 0.1 Hz cyclic stress of 1475 N amplitude at a fixed normalized H of 0.267. The demonstrated result suggest relatively good quantitative match between measured and computed values.

It should be stated out that given a 15 turn pick up coil wound around the sample and knowing the sample cross section area, it is possible to infer the harvested induced voltage as a result of the mechanical vibration.

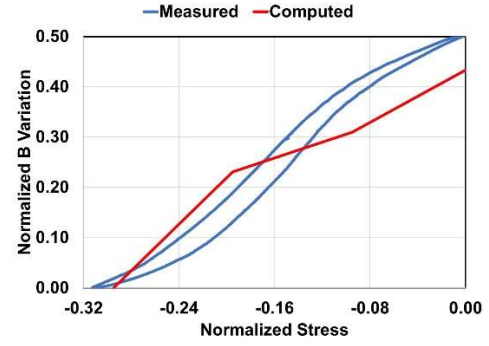


Fig. 3. Comparison between measured and computed B variation due to applied cyclic mechanical stress of amplitude 1500 N while maintaining H at a normalized value of 0.267.

III. CONCLUSION

An efficient approach for the modeling and simulation of electrical energy harvesting using magneto-elastic materials has been presented. Simulations to assess the model accuracy in predicting B - H curves for different applied mechanical stress as well as for energy harvesting demonstrated good overall qualitative and quantitative match. More details on the model capability to predict energy harvesting waveforms will be presented in the full paper.

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