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A unified framework for modeling hysteresis in ferroic materials

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Abstract

This paper addresses the development of a unified framework for quantifying hysteresis and constitutive nonlinearities inherent to ferroelectric, ferromagnetic and ferroelastic materials. Because the mechanisms which produce hysteresis vary substantially at the microscopic level, it is more natural to initiate model development at the mesoscopic, or lattice, level where the materials share common energy properties along with analogous domain structures. In the first step of the model development, Helmholtz and Gibbs energy relations are combined with Boltzmann theory to construct mesoscopic models which quantify the local average polarization, magnetization and strains in ferroelectric, ferromagnetic and ferroelastic materials. In the second step of the development, stochastic homogenization techniques are invoked to construct unified macroscopic models for nonhomogeneous, polycrystalline compounds exhibiting nonuniform effective fields. The combination of energy analysis and homogenization techniques produces low-order models in which a number of parameters can be correlated with physical attributes of measured data. Furthermore, the development of a unified modeling framework applicable to a broad range of ferroic compounds facilitates material characterization, transducer development, and model-based control design. Attributes of the models are illustrated through comparison with piezoceramic, magnetostrictive and shape memory alloy data and prediction of material behavior.

Keywords: Ferroic materials; Unified models; Hysteresis; Constitutive nonlinearities

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1. Introduction

Ferroelectric, ferromagnetic and ferroelastic materials share a number of mesoscopic and macroscopic attributes including the formation of analogous domain structures and the presence of hysteresis and constitutive nonlinearities as illustrated in Fig. 1. While hysteresis and constitutive nonlinearities are inherent to all presently employed ferroic compounds, the degree and severity of these effects can often be mitigated by restricting drive levels, employing appropriate drive electronics, or incorporating feedback loops in transducers. In many applications, however, hysteresis and material nonlinearities are unavoidable and must be incorporated in models and subsequent control designs to achieve the full capabilities of the materials. To illustrate, we consider the behavior of certain representative ferroelectric, ferromagnetic and ferroelastic materials employed in present high performance transducer applications.

Piezoceramic actuators are employed for nanoscale positioning due to their high set point accuracy and broadband capability. In present atomic force microscope (AFM) or scanning tunneling microscopic (STM) designs, PID or robust control laws are employed to mitigate hysteresis in the relation between input fields or voltages and strains generated by the device (Salapaka et al., 2002; Schitter et al., 2001). This is effective for low scan rates and has led to the phenomenal success of the devices. However, at the higher scan rates

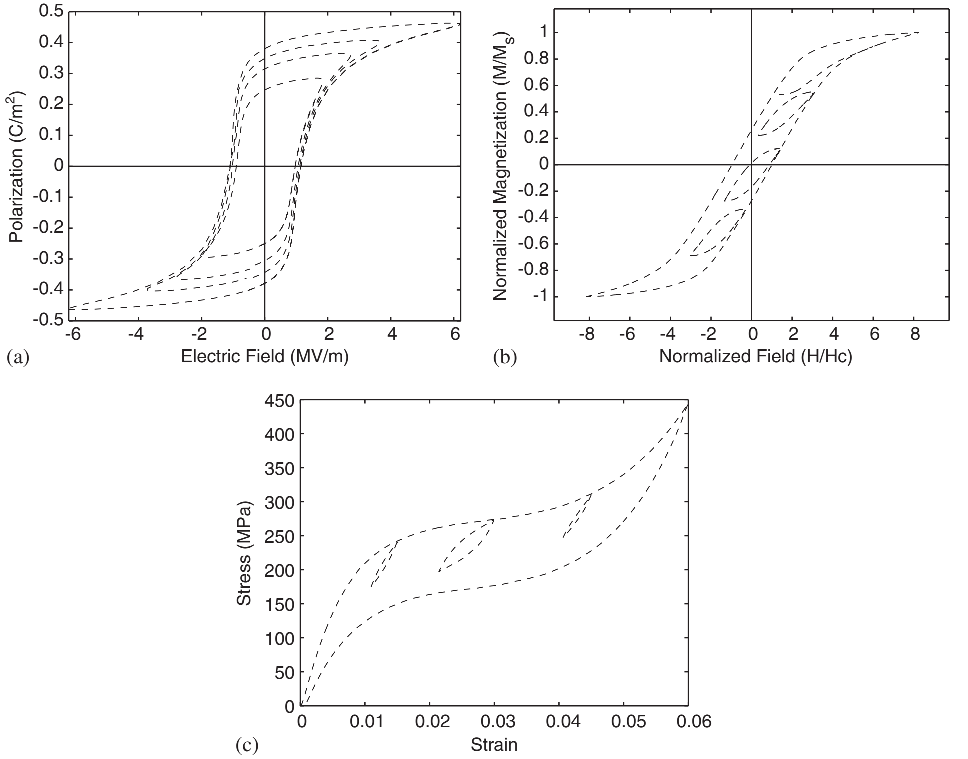

Fig. 1. Hysteresis and constitutive nonlinearities exhibited by various ferroic compounds: (a) PZT5A data; (b) Terfenol-D data; (c) NiTi data.