Preface

Writing a book on smart materials bears a certain semblance to purchasing a high-end laptop — due to rapid advances in the field, it is tempting to postpone the decision every six months in order to include the latest technological development. At some point, however, one must simply focus on the present technology and realize that upgrades will be necessary in the future.

The field of smart materials has advanced rapidly in the last 15 years due to an increasing awareness of material capabilities, the development of new materials and transducer designs, and increasingly stringent design and control specifications in aerospace, aeronautic, industrial, automotive, biomedical, and nano-systems.

Equally important for the advancement of the field is the development of models, numerical approximation techniques, and control designs which accommodate the hysteresis and constitutive nonlinearities inherent to the materials. The majority of initial investigations focused on linear analysis based on the approximately linear material behavior observed in low to moderate drive regimes and obtained with certain amplifier and feedback designs. When applicable, linear models and control designs are certainly advantageous and should be considered first. However, for an increasing number of applications, the attributes which provide smart materials with unique actuator and sensor capabilities are inexorably due to physical mechanisms that produce hysteresis — hence these mechanisms must be incorporated in models and control designs to achieve the unique performance capabilities offered by the compounds. For example, the damping provided by shape memory alloy tendons in civil and aerospace structures is proportional to the area of the hysteresis loop. Hence optimal vibration attenuation requires optimal hysteresis which is diametrically opposite to the strategy of operating in approximately linear regimes.

In this monograph, we provide a unified development of linear and nonlinear models for smart material systems as a prelude to model-based control design. We focus significant attention on the physical mechanisms that provide the materials with unique transducer capabilities but yield hysteretic and nonlinear behavior, and, to the extent possible, we use the underlying physics to guide the development of unified constitutive frameworks for quantifying the dynamics of a broad class of ferroic compounds. These constitutive relations are subsequently employed to construct structural models for a range of transducer constructs and geometries. Finally, we address the development of numerical approximation techniques which

adhere to the physical principles used to construct models and are appropriate for transducer and control design.

In Chapter 1, we summarize a range of present and projected smart material applications to illustrate both the scope of the field and issues that must be addressed in models. Chapters 2–5 address the development of linear and nonlinear models for ferroelectric, ferromagnetic and ferroelastic compounds. In each of these chapters, we discuss three classes of nonlinear models — Preisach models, domain wall models, and homogenized energy models — since they comprise unified frameworks for the combined class of ferroic compounds, as illustrated in Chapter 6, and are amenable to control design. Whereas all three frameworks encompass physical principles, we focus primarily on the third since the combination of lattice-level energy principles and stochastic homogenization to incorporate material nonhomogeneities provide it with extreme flexibility in a range of smart material applications and operating regimes. It is illustrated in Chapters 2 and 4 that the homogenized energy framework provides an energy basis for extended Preisach formulations. It is thus anticipated that the symbiotic investigation of energy-based and extended Preisach models will strongly contribute to the growth of unified characterization frameworks with the former providing strengths inherent to the energy basis and the latter providing a mature mathematical framework for model analysis and identification.

The unified constitutive models developed in Chapters 2–6 provide the nucleus for the linear and nonlinear rod, beam, plate and shell models detailed in Chapter 7. In this manner, relevant physics is incorporated in the system models to augment accuracy and improve efficiency as required for real-time implementation. Chapter 8 summarizes numerical approximation techniques that are appropriate for both simulations and control design.

The topic of model development for smart material systems is highly interdisciplinary and this book was written with the goal of making it accessible to scientists from a broad range of disciplines with backgrounds ranging from students entering the field to experts within the constituent disciplines. To aid the understanding of both mathematical and physical terminology, we have included numerous definitions throughout the text and have provided an extensive glossary of terms in an appendix. We have also placed mathematical proofs in an appendix so they are available for those who are interested but do not deter readers focusing primarily on physical aspects of the theory. Finally, open research questions are indicated at various points to encourage investigations deemed necessary to advance the state of knowledge in this rapidly evolving field.

Whereas the text does not include exercises, preliminary versions have been used in graduate courses on smart material systems and much of the detail provided throughout the book was motivated by feedback from students in those classes.

Various resources will be maintained at the website `http://www.siam.org/ books/fr32` to augment the text and provide a mechanism to update the material. To aid the reader in the implementation of certain models, we have included MATLAB® m-files for the homogenized energy framework used to characterize hysteresis in ferroelectric, ferromagnetic and shape memory alloy compounds as well as well as rod, beam and plate codes. Whereas these are research rather than

commercial-level codes, they illustrate facets of the models and will provide a template for simulating the behavior of various smart material systems. We will also maintain a list of errata and certain updates to the material at this website.

The reader will note that while a number of smart materials are discussed in Chapter 1, the model development in subsequent chapters focuses almost exclusively on ferroelectric, relaxor ferroelectric, ferromagnetic and ferroelastic compounds. Although this includes a large cross-section of presently employed materials, it neglects a number of established and emerging compounds such as ionic and amorphous polymers, MR and ER fluids and solids, and fiber optic sensors. This omission is dictated solely by the unified nature of ferroic compounds, in addition to length limitations, and should not be construed as an indication of material merit. Numerous references are provided in Chapter 1 to guide readers investigating applications which exploit alternative materials.

A significant body of this research resulted from collaborations with students, postdocs and colleagues, and credit to their contributions is liberally given through the citations. Special thanks are also extended to collaborators whose comments on preliminary versions of the manuscript have significantly improved the exposition and reduced the number of typos by several orders of magnitude. Specifically, sincere thanks are given to Brian Ball, Lynn Boyles, Tom Braun, Marcelo Dapino, Andrew Hatch, Emily Lada and Stefan Seelecke for their attention to detail and honest feedback when reading parts of the manuscript. Andrew Hatch and Jordan Massad are credited with writing and editing much of the software that is included at the text website to render it in a form that is friendlier to users.

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