Preface

Several decades have passed by since the discovery and development of micro-electro-mechanical systems (MEMS). This technology has reached a level of maturity that, today, several MEMS devices are being used in our every-day life, ranging from accelerometers and pressure sensors in cars, micro-mirrors in Plasma TVs, radio-frequency (RF) switches and microphones in cell phones, and inertia sensors in video games. Fabrication methods of MEMS, such as bulk and surface micromachining, are now well-known and almost standardized. Nowadays, hundreds of foundries around the world offer numerous fabrication services that can translate the imagination of a MEMS designer of a device into reality.

Even with the maturity of fabrication and commercialization, MEMS is still one of the hottest evolving areas in science and engineering, where scientists from across various disciplines investigate, brainstorm, and collaborate to invent smarter devices, develop new technologies, and innovate unique solutions. With the increasing pressure for sensors and actuators of sophisticated functionalities, which are self-powered, self-calibrated, and self-tested, MEMS are expected to remain the sought-after technology of scientists for many years to come.

However, with this growing demand on the MEMS technology come great challenges. Designers are now aiming to achieve complicated objectives while meeting a long list of specifications related to sensitivity, fabrication, system integration, packaging, and reliability. These challenges have created a motivation to seek new solutions and ideas, beyond changing the geometry of devices and making more complex configurations. Researchers are starting to realize the need to look into new methods of improvement and innovation in MEMS beyond the static laws of design and the limitations of linear theories. It is realized now that linear theories are too shallow to allow for bolder ideas and more aggressive design goals. More attention is being directed to investigate deeply the dynamics and motion aspects of MEMS and to explore the hidden opportunities of operating MEMS in the nonlinear regimes.

Most MEMS devices employ a structure or more that undergoes some sort of motion. Accelerometers, gyroscopes, micromirrors, microphones, resonators and oscillators, RF switches and filters, and thermal actuators are few examples of such. Hence, it comes no surprise that the motion characteristic of microstructures affect directly the specifications, quality, and limitations of MEMS devices. Unfortunately, however, understanding the motion aspects of these devices is not a trivial task, which is one of the reasons that have delayed the research attention in this area.

Many microstructures are highly compliant. When actuated, they undergo large deflection or deformation compared to their dimensions. This amplifies the geometric nonlinearity of the structures. Microstructures are commonly actuated by parallel-plate electrostatic forces, which are inherently nonlinear. When microstructures are driven to motion, they may experience nonlinear dissipation mechanisms, such as squeeze-film damping. These various nonlinear sources in MEMS play significant role in their response and performance. As a result, models and designs based on linear theories can be inadequate, inaccurate, and incorrect. Further, the interaction among inherent coupled-physical domains, such as mechanical, electrostatic, thermal, and fluidic, marks one of the key features of MEMS. This coupling can further complicate the design process. In addition, new phenomena that are common in the microscale range, such as squeeze-film damping and pull-in instability, add to these difficulties. Tackling multiphysics, nonlinear, and dynamic problems can be very challenging especially in the presence of instabilities, such as pull-in, which can cause serious convergence problems in commercial simulation software.

These new challenges facing MEMS designers and researches combined with the growing interest in MEMS and their dynamical behavior have been the motivation behind this book. This book has two main goals: First is to provide the necessary analytical and computational tools that enable students and professionals to model the static and dynamic behavior of MEMS accurately in multiphysics fields and accounting properly for their nonlinearities. The second goal is to present in-depth analysis and treatment for the most common static and dynamic phenomena in MEMS encountered by MEMS engineers and researchers, especially those associated with electrostatic MEMS.

The organization of the book material is as follows: Chapter 1 introduces MEMS, their features, and some of their modeling and simulation challenges and needs. Chapter 2 discusses the basic principles of the vibrations of single- and multiple-degrees-of-freedom systems. Free vibrations and forced vibrations in response to harmonic and arbitrary forcing are discussed. Chapter 3 introduces the common sensing and actuation methods in MEMS. These include electrothermal, piezoelectric, electromagnetic, piezoresistive, and electrostatic methods. The rest of the chapter is dedicated to illustrate the theory of electrostatic transduction in parallel-plate capacitors, torsional actuators, and comb-drive devices. Chapter 4 discusses the basic elements of lumped-parameter modeling, which are the stiffness elements, effective mass, and damping mechanisms including squeeze-film, slide-film, and thermoelastic damping.

Chapter 5 builds on the background of Chaps. 1–4 to introduce the reader to basic principles of nonlinear dynamics and stability analysis as applied to MEMS applications. In doing so, several common phenomena at the microscale are introduced and illustrated, such as pull-in, side instability of comb fingers, collapse due to capillary forces, dynamic pull-in, and hysteresis. Analytical methods, such as linearization and phase diagrams, are illustrated. Then the chapter discusses nonlinear oscillations with emphasis on the qualitative features and main differences compared to the linear vibrations of Chap. 2.

Moving from lumped-parameter to distributed-parameter modeling, Chap. 6 is dedicated to the most common and essential structures in MEMS: microbeams. Using a Newtonian approach, the chapter starts with a discussion on the derivation of the linear equation of motion and various kinds of boundary conditions. The static problem is discussed followed by illustration of solving the eigenvalue problem to extract the natural frequencies and modeshapes of common beams. Then, forced vibrations and the modal analysis procedure are presented. The second half of the chapter deals with nonlinear models of beams with emphasis on midplane stretching and electrostatic nonlinearities. The Galerkin procedure and reduced-order modeling are then discussed. As an application, universal pull-in curves of electrostatically actuated microbeams are presented. Following the static simulations, methods to solve the eigenvalue problem of beams under electrostatic actuation and the forced vibration response due to AC and DC actuation are discussed. Modeling of Atomic Force Microscopes is then presented. The chapter ends with discussions on the modeling of damping in beams.

Chapters 7 and 8 present special case studies of importance in MEMS, which are treated in some depth both theoretically and experimentally. Chapter 7 discusses the nonlinear dynamics of electrically actuated resonators. Simulation methods, such as the shooting technique and the basin-of-attraction analysis, are introduced and demonstrated. Dynamic pull-in, its utilization, and control are discussed. Chapter 8 deals with a reliability topic, which is the response of MEMS to mechanical shock. Modeling shock in MEMS, its interaction with electrostatic forces and printed circuit boards, and details on experimental testing are presented.

This book can be used by professionals of all levels who aim to model and simulate the behavior of MEMS devices and structures or to improve their design for static and dynamic considerations. In addition, the book serves as an excellent reference to enable full understanding of common MEMS phenomena that face MEMS engineers and researchers, such as squeeze-film damping, buckling, and pull-in instability. The depth of treatment of many of the topics covered in this book should appeal to MEMS researchers and those who consider doing research in related fields.

The book can be used as a text for two courses related to MEMS modeling and design or more specifically for courses in the statics and dynamics of MEMS. Chapters 1–4 and some of the material of Chap. 5 can be used for a first-year graduate or senior undergraduate course. For students who are familiar with mechanical vibrations, many of the materials of Chap. 2 can be assigned for self-reading except for topics specific to MEMS applications, such as MEMS gyroscopes, accelerometers, and band-pass filters. Chapters 5–8 suit a second-year graduate course. In addition, instructors are recommended to add research-oriented projects to encourage students to explore what is new in this highly dynamic field.

The author has relied on introducing and illustrating many new concepts and analytical and numerical approaches through examples instead of introducing them as abstract theories. While this approach does not provide much mathematical rigor, from the author's experience, it is easier for the students to digest. This is especially true for those outside the mechanical engineering and nonlinear dynamics disciplines. The examples of the book range in their complexity from simple to more difficult and research-oriented ones. These are not intended for beginners in the field but rather for advanced researchers and graduate students. The author aims of such examples to stimulate deep thinking and motivate further research in the field.

A note worth to be mentioned here is regarding the cited references in the book. While the author has attempted to present numerous references for researchers and interested scientists on the various discussed topics, these are not complete lists and do not represent the full spectrum of the state of the art. These references should be considered only as a good starting point for those who want to follow research in related topics.

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