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Introduction

In this introductory chapter, the concepts of microsystems, dynamics/vibrations, and microsystem dynamics are described. Then the significance of microsystem dynamics in engineering, science, and everyday life is presented. In the last section, the organization of the book is introduced.

1.1 Definition of Microsystem, Vibrations and Dynamics

Microsystems or microelectromechanical systems (MEMS) are miniaturized devices with components measured in micrometers that perform micro- to nanometer scale electronic machine functions such as sensing and actuation. Typical microsystems have both mechanical and electrical parts, like read-write heads in computer storage devices, or bending cantilevers in atomic force microscopes [1–13].

Vibration studies the oscillatory motion of an object around an equilibrium point and the forces associated with it. The oscillations may be periodic or random. The associated forces may be linear or nonlinear. Vibration is usually detrimental, and occasionally “desirable” for engineering systems. Dynamics studies the movement of systems of interconnected bodies under the action of external forces. For rigid-body dynamics, the moving bodies are assumed to be rigid, which simplifies the analysis by reducing the parameters that describe the configuration of the system to the translation and rotation of reference frames attached to each body. The dynamics of a rigid body system are defined by its equations of motion, which are derived using either Newton–Euler equations or Lagrangian equations. The dynamics of a flexible body system or structural dynamics have general dynamical equations of motions, including stress and strain relations.

Unlike most conventional engineering systems, in microsystems, surface-related forces play significant roles and are not ignorable compared with body forces. A microsystem with moving parts functionally operates with varied movements and thus involves vibrations and dynamics. Numerous models have been developed for varied microsystems under individual conditions. Microsystems and vibration/dynamics used to be two distinct fields. However, with the recent rapid developments in dynamical microsystems – especially the extensive applications of dynamical microsystems in IT hardware, telecommunications, biomedical technology, manufacturing and robotic systems, transportation, and aerospace, engineers are turning to combining microsystem and dynamics/vibrations for integrated and efficient methods to handle and analyze the vast amounts of practical cases.

This book, *Microsystem Dynamics*, offers a combined treatment of the modeling, analysis, and testing of many problems that application engineers are trying to solve. After delineating these mathematical characterizations, it presents several applications in use today for analyzing microsystem dynamics. Emphasis is put on the contemporary knowledge and perspectives of microsystem dynamics.

1.2 Engineering and Scientific Significance of Microsystem Dynamics

Several decades have passed since the discovery and development of microsystems. Microsystem technology is beginning to explode with extensive applications.

Varied microsystems are used in numerous scientific and engineering systems and our everyday life. Just to name a few: active sliders in computer hard disk drives; accelerometers and pressure sensors in vehicles; lithium-ion batteries in electric vehicles; micromirrors in TVs; radiofrequency switches and MEMS microphones in cell phones; varied microactuators, such as MEMS valves, pumps, and microfluidics; electrical and optical relays and switches; MEMS grippers, tweezers, and tongs; MEMS linear and rotary motors; inkjet printer heads; microvehicles (e.g. microaircraft, microcars). After several decades of development, the fabrication methods of bulk and surface micromachining for microsystems are now matured and almost standardized.

The examples of microsystem dynamics phenomena cover numerous mechanisms in science and engineering. Even in laptops, we rely on dynamic microsystems for data storage and retrieval. Microsystem dynamics extend beyond engineering applications, it includes numerous phenomena in science and nature. This book considers microsystem dynamics in its broader meaning yet concentrates on fundamentals and engineering applications.

To give some examples of the problems treated in the book, let's consider the immense efforts that are being put into dealing with microsystem dynamics in the information storage industry, lithium-ion battery industry, and microactuator industry.

We are living in an information age. The needs for information storage systems are tremendously high and ever-increasing. There are a variety of information storage systems with varying degrees of development and commercialization. To date, magnetic information storage technology, particularly hard disk drives, is the most widely used. We are all familiar with computers in which the hard disk is one of key components. The worldwide hard disk drive revenue had reached \$50 billion. Magnetic hard disk drives are based on the same fundamental principles of magnetic recording which involves a recording head and a recording medium. The former is on a suspension-supported slider, while the latter is on a spinning disk. The slider is flying on the spinning disk with the air gap. The operation of the hard disk drive is based on a self-pressurized air-bearing between the slider and the spinning disk, which maintains a constant separation called flying height. The state-of-the-art flying height is on the order of below 10 nm, while the relative speed between the slider and disk is extremely high (20 m/s or higher). The mechanical spacing between the slider and the disk must be further reduced to less than 2 nm to achieve an areal density beyond 1 Tbit/in². In these regimes, microsystem dynamics have been the most challenging and critical problem for the products. On the other hand, over the last decade, the microsystem dynamics technique have been one of the most important techniques to advance slider disk interface and hard disk drive technology.

Rechargeable lithium-ion batteries (LIBs) have been used for a wide variety of applications from small-scale portable electronics to massive-scale energy storage systems. Particularly, electric vehicle battery building has been booming worldwide for the last several years. The market value of the LIBs industry was about \$55 billion in 2023. With the enhanced demand for LIBs, experts predict this market will grow steadily, with a compound annual growth rate of around 20% from 2024 to 2030. A typical LIB cell is made up of an anode, cathode, separator, electrolyte, and two current collectors (positive and negative). The anode and cathode (both with thickness between 50 and 100 μm) store the lithium. The electrolyte carries positively charged lithium ions from the anode to the cathode and vice versa through the separator. The movement of the lithium ions creates free electrons in the anode which creates a charge at the positive current collector. The electrical current then flows from the current collector through a device being powered (cell phone, computer, vehicle motor, etc.) to the negative current collector. The separator (with a thickness between 20 and 30 μm) blocks the flow of electrons inside the battery. While LIB is discharging and providing an electric current, the anode releases lithium ions to the cathode, generating a flow of electrons from one side to the other. When plugging in the used LIB to the electrical grid for charging, the opposite happens: lithium ions are released by the cathode and received by the anode. However, the existing problems of LIBs limit their reliable applications in vehicles due to the stringent safety standards. The limitations of current battery technology include underutilization, capacity fade, thermal runaway, stress-induced fracture, and microscale material damage. To overcome these challenges, understanding the complex multiphysics and multiscale dynamics of LIBs is indispensable.

Microactuators or MEMS actuators are devices that convert electrical energy to mechanical motion, which comprise more than 50% of the rapidly growing microsystems/MEMS market which has a worldwide revenue of about \$20 billion. Microactuators are widely used in science and engineering. Examples include variable capacitors, microrelays for low-power VLSI, optical phase shifters, next-generation displays, microgrippers for robotic surgery, and focusing mechanisms for cameras in mobile devices. There are various microactuators using different dynamical systems, which are characterized by microsystem dynamics with various electrostatic, thermal, piezoelectric, and magnetic features.

Understanding the nature of microsystem dynamics and solving the technological problems associated with microsystem dynamics are the essence of these fields.

Modeling of microsystem dynamics in engineering and scientific systems requires an accurate description of microsystems and dynamics. Unfortunately, this is extremely challenging as it involves complex surface phenomena in microscales. On the other hand, the resultant vibrations and dynamics in microsystems often exhibit various nonlinear, nonstationary, and uncertain features due to complex surface or interfacial forces. Moreover, small changes in interfacial parameters could have significant effect on the resultant vibrations and dynamics, thus, the scales of influencing factor span from macro-, micro-, to nanometer levels. The boundary condition of the problems is not fixed or given in prior, it is dependent on environmental conditions, operation conditions, system interactions, and dependent on time. Because of the complexity of the problems, tremendous efforts have been made in many engineering and scientific communities.

The recent extensive efforts in modeling, analytical, and experimental investigation have made a lot of substantial progress in many practical applications. Many advanced techniques of measurement, nonlinear dynamics, signal processing, computational intelligence, and system identification have been used as efficient means to address nonlinear, nonstationary, and uncertain vibrations and dynamics, which enables to efficiently quantify microsystem dynamics and

leads to the development of the insight of microsystem in micro, nano, molecular, or even atomic scales.

The purpose of research in microsystem dynamics lies in many ways, just to name a few: to develop a fundamental understanding of dynamical microsystems; to make use of its principle to design novel engineering microsystems; to make use of the microsystem dynamics to explore phenomena in complex process where the other means are not accessible; and understandably to reduce and eliminate the instability and vibrations in engineering microsystems thus enhance the durability, reliability and safety of products.

1.3 Organization of the Book

The book has been set out with a twofold aim in view. The first aim is to give a general introduction to the theory of vibrations, dynamics, and surface and interface interactions at the microscale, offering a physical picture of the fundamental theory. The second aim is to give a series of examples of the applications of the theoretical approaches. The author is expected to provide contemporary coverage of the primary concepts and techniques in the treatment of microsystem dynamics.

This book brings together into one accessible text the fundamentals of the many disciplines needed by today's engineers working in the field of microsystem dynamics. This book consists of six chapters. The basic principles of vibrations, dynamics, surface forces and interactions, and critical applications of microsystem dynamics are introduced in these chapters. Chapter 1 introduces the whole book. Chapter 2 provides a comprehensive introduction to the analysis of vibrations and dynamics, from vibrations of linear systems, and random excited systems to nonlinear systems and rigid-body dynamics by covering most required areas and applications. Chapter 3 describes the principles of surface forces and interface interactions in macro- and microscales. In Chapter 4, the concepts and methods are extended to the most critical engineering applications of microsystems in the IT industry. It presents the microsystem dynamics of microscale air-bearing slider systems and nanoscale MEMS slider systems, which are widely used computer hard disk drive. Chapter 5 presents the microdynamics of lithium-ion batteries in the context of multiphysics, which has been widely investigated in science and engineering communities for extensive applications recently. In Chapter 6, the microsystem dynamics of varied MEMS actuators are presented.

Complete references given in the book provide a comprehensive perspective on the developments in microsystem dynamics, as well as covering various applications. For didactical reasons, the text is not interrupted by the inclusion of references. However, at the end of each chapter, the relevant literatures published are cited.

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