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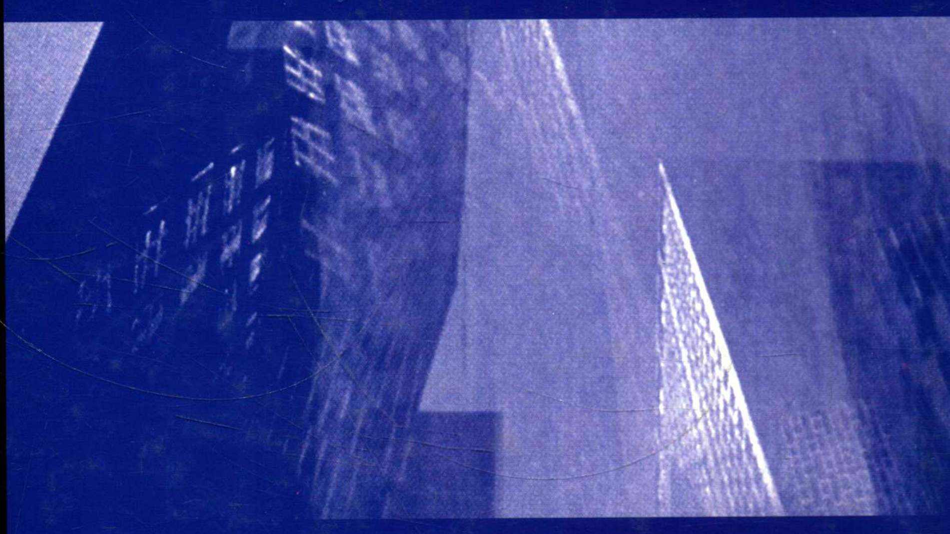
Chee-Kiong Soh • Yaowen Yang
Suresh Bhalla *Editors*

Smart Materials in Structural Health Monitoring, Control and Biomechanics



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Preface

Smart materials, perhaps the most fascinating category of materials developed in the 20th Century, possess responsive capabilities to external stimuli, enabling them to change their physical properties according to the stimulus. The feedback functions within the materials are combined with the properties and functions of the materials. Smart materials can be either "*active*" or "*passive*". Active smart materials, one hand are those which possess the capacity to modify their geometric or material properties under the application of electric, thermal or magnetic fields, thus acquiring an inherent capacity to transduce energy. Piezoelectric materials, shape memory alloys, electro-rheological fluids and magneto-strictive materials are active smart materials which can be used as force transducers and actuators. Additionally, piezoelectric materials can convert mechanical force into electrical energy, enabling them as sensors or energy harvesters. Passive smart materials, on the other hand, lack the inherent capability to transduce energy, *e.g.*, fiber optic material. Such materials can act as sensors but not as actuators. This book examines both active and passive smart materials in structural health monitoring (SHM), control and bio-mechanics. The book starts with the fundamentals and takes the readers gradually through the mathematical formulations and experimental details.

Chapters 1 to 7 of the book are primarily concerned with the lead zirconate titanate (PZT) piezoelectric material and the electro-mechanical impedance (EMI) technique for SHM. The different impedance models, derived by the book's authors, for health monitoring and damage quantification using PZT transducers are presented. This includes three approaches: extraction of structural mechanical impedance from signatures; identification of higher natural frequencies from signatures; and the use of evolutionary programming. Furthermore, strength and damage assessment of concrete using both surface-bonded and embedded PZT transducers are examined. The extracted equivalent stiffness is used in a framework of fuzzy set theory to spell out a damage quantification approach for real-world concrete structures. An approach to integrate the EMI technique with global vibration techniques is also presented. It is shown that the same PZT patch can serve as the sensor for both techniques. Whereas incipient-level damages can be identified using the EMI technique, the global vibration response of the structure acquired from the same patch with minimal hardware and data processing tools can facilitate the detection, localization and quantification of moderate to severe damage. Finally, several practical issues involving the application of PZT transducers and EMI technique for SHM such as sensing region and load monitoring are discussed.

Chapters 8 to 10 of this book focuse on the control and excitation of structural vibration using piezoelectric transducers. Analytical and semi-analytical solutions for vibration control of smart beams, subjected to axial loads, are derived under different control strategies. The integrated optimization of the control system for smart plates and shells is then formulated and implemented using a modified genetic algorithm (GA). Numerical results illustrate that vibration suppression could be significantly enhanced with the appropriate distribution of piezoelectric transducers and selection of control parameters. Subsequently, the optimal excitation of plates and shells using PZT transducers is demonstrated and a simple, yet general, procedure to determine the optimal excitation locations of the PZT actuators is presented. Finally, the dynamic response of a fully coupled hybrid piezo-elastic cylindrical shell with piezoelectric shear actuators is presented, followed by investigation of the active vibration control of the cylindrical shell.

Use of the passive smart material, fiber optic, as sensors for SHM is covered in Chapters 11 to 13. After a presentation of the theoretical details, real-life applications of fiber Bragg grating (FBG) sensors—the most successful type of fiber optic sensor in the health monitoring of highway bridges and rock and underground structures—are presented. In addition, comparisons between monitoring of rock and underground structures using FBG and electrical strain gauges (ESGs), and FBG and PZT are made.

Use of another active smart material, ionic polymer-metal composite (IPMC), in bio-mechanics is discussed in Chapters 14 to 16. The bending capacity of IPMC is first derived and validated under both dynamic and static electric potentials, followed by the modeling of an IPMC beam on human tissue, an IPMC ring with elastic medium and an IPMC shell with flowing fluid, which represent possible applications of IPMC materials in biomedical engineering. Examples are also used to illustrate the viability of the models. Lastly, application of PZT transducers as bio-medical sensors to characterize bones is presented. The study is verified with finite element (FE) simulation of the EMI technique on bones.

Chapter 17 completes the book by looking into the future use of smart materials. Based on preliminary works done by the book's authors, the future application of IPMC as artificial muscles and organs, and the future application of PZT, macro-fiber composite (MFC) and IPMC for harvesting of ambient energy are envisaged.

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Contents

1 Introduction

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1.1 Overview

Civil infrastructures are important long-term investments of a nation which are crucial in supporting the nation's economic and social activities. Therefore, it is vital to continuously monitor the performance and condition of all civil infrastructures, especially the critical ones such as bridges and power plants so that any adverse changes in their performance or condition can be detected in a timely fashion and mitigated. In addition, instrumenting the structures at the time of construction, and their monitoring thereafter, could help in validating key design parameters as well as providing valuable insight into their behavior and performance under actual loadings. Ironically, whereas vast economic resources are mobilized for the construction of civil infrastructures, structural engineers in general are not too concerned with their post-construction behavior.

During the last one and a half decades, the idea of monitoring structures through appropriate instrumentation has gained wide acceptance. The approach is similar to monitoring the critical parameters of an aircraft during flight or an automobile on the road, so that any malfunctions can be detected early, thereby facilitating pre-emptive action. Hence, the need for structural health monitoring (SHM) has become widely acknowledged. Generally, SHM is defined as the measurement of the operating environment and critical responses of a structure to track and evaluate the symptoms of operational incidents, anomalies, and deterioration or damage indicators that may affect operation, serviceability, safety or reliability (Aktan *et al.*, 2000). It implies continuous monitoring, acquisition, validation and analysis of technical data to facilitate life-cycle management decisions (Kessler *et al.*, 2002). A subset of SHM is condition assessment, which is defined as the periodic or one-time establishment of the current conditions, specifically aimed at assessing fitness for purpose. Several bridges have been instrumented for SHM or condition assessment in recent years. Most notable among them are the I-40 bridge in New Mexico (Farrar and Jauregui, 1998), the Second Link bridge connecting Malaysia and Singapore (Moyo, 2002), the Tsing Ma suspension bridge in Hong Kong (Lynch *et al.*, 2003) and the Boujnah bridge of the Tunis-Msaken Highway (El-Borgi *et al.*, 2005).

Several algorithms have been proposed to locate and determine the severity of damage in bridge structures based on their vibration response. In these techniques, essentially the test-structure is subjected to low-frequency excitations, either harmonic or impulse, and the resulting vibration responses (displacements, velocities or accelerations) are picked up at specified locations along the structure. The vibration pick-up data are processed to extract the first few mode shapes and the corresponding natural frequencies of the structure, which, when compared with the corresponding data for the healthy state, yield information pertaining to the locations and the severity of the damage. Application of this principle for damage detection can be found as early as in the 1970s (*e.g.* Adams *et al.*, 1978). Subsequently, this concept was employed for structural system identification, a mathematical model of the structure from the experimental input-output data (*e.g.* Yao, 1985; Oreta and Tanabe, 1994; Loh and Tou, 1995). It should be mentioned that several of these techniques consist of "updating" a numerical model of the structure from test measurements. In the 1990's, with the development of improved sensors, testing hardware, and data acquisition and processing techniques, many "quick" algorithms have been proposed (mainly for bridge type structures), such as the change in *curvature mode shape* method (Pandey *et al.*, 1991), the *change in stiffness* method (Zimmerman and Kaouk, 1994), the *change in flexibility* method (Pandey and Biswas, 1994) and the *damage index* method (Stubbs and Kim, 1994). A comparative evaluation of these algorithms on an actual bridge structure, by Farrar and Jauregui (1998), revealed the *damage index* method to be the most sensitive among these methods. However, only limited studies have been conducted on buildings and offshore structures (Thompson and Harper, 2004; Sun *et al.*, 2007), which exhibit a behavior of far greater complexity. The search for more durable and cost-effective sensors and hardware is far from over on account of the limitations of existing technologies and methods, especially when applied on real-life structures (Catbas *et al.*, 2007). The main limitations of the global dynamic techniques can be summarized as follows:

(1) These techniques typically rely on the first few mode shapes and the corresponding natural frequencies of structures, which, being global in nature, are not sensitive enough to be altered by localized incipient damages. For example, Pandey and Biswas (1994) reported that a 50% reduction in the Young's modulus of elasticity, over the central 3% length of a 2.44 m long beam (as an example),