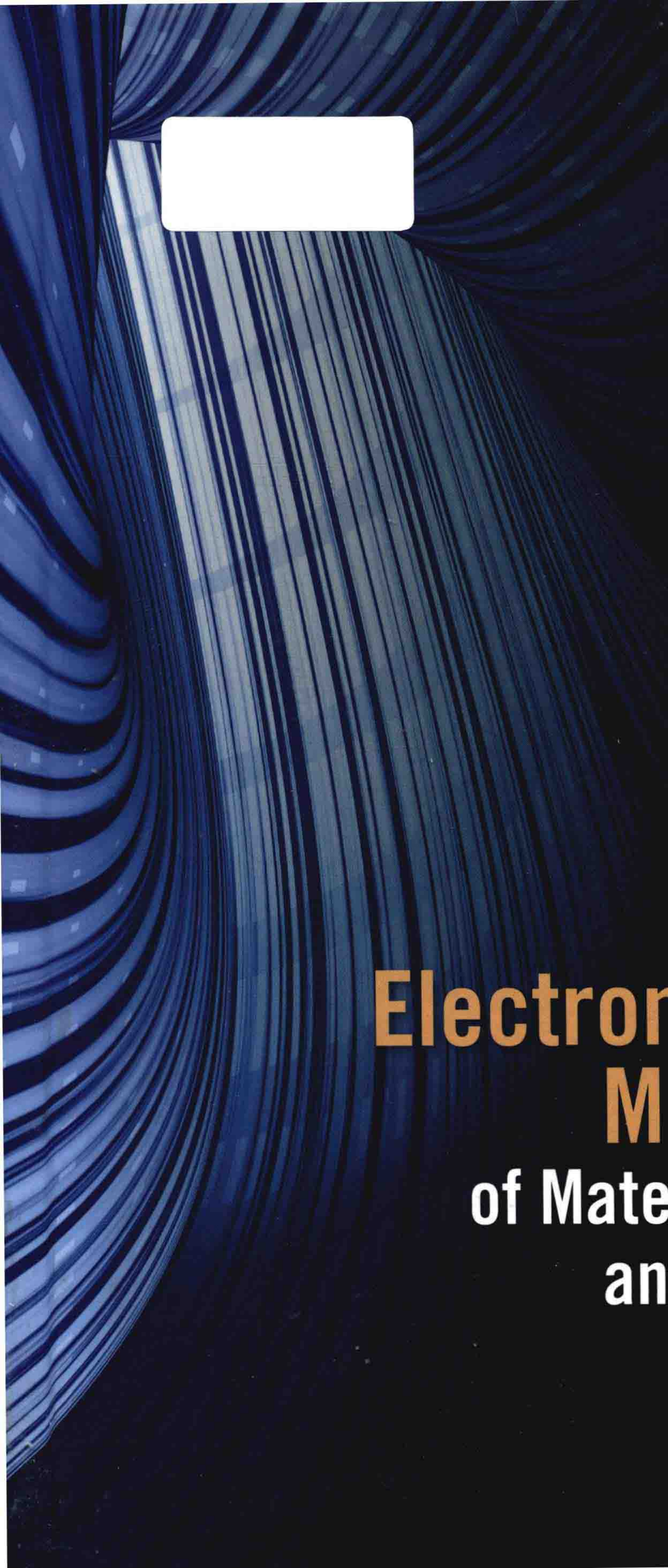

YASUHIDE SHINDO

# Electromagneto-Mechanics of Material Systems and Structures

WILEY

# ELECTROMAGNETO-MECHANICS OF MATERIAL SYSTEMS AND STRUCTURES

**Yasuhide Shindo**
*Tohoku University, Japan*



WILEY

This edition first published 2015


*Registered office*
John Wiley & Sons Singapore Pte. Ltd., 1 Fusionopolis Walk, #07-01 Solaris South Tower, Singapore 138628.

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.



*Library of Congress Cataloging-in-Publication Data applied for.*

ISBN: 9781118837962

Set in 10/12pt, TimesLtStd by SPi Global, Chennai, India.
Printed and bound in Singapore by Markono Print Media Pte Ltd

1 2015

# ELECTROMAGNETO-MECHANICS OF MATERIAL SYSTEMS AND STRUCTURES

# About the Author

Dr. Shindo received his Doctorate of Engineering from Tohoku University in 1977. He is currently a professor in the Department of Materials Processing in the Graduate School of Engineering at Tohoku University. Dr. Shindo also served on the Board of Editors of the *International Journal of Solids and Structures* and is currently serving on the editorial board of *Journal of Mechanics of Materials and Structures*, the Advisory Board of *Acta Mechanica*, the International Editorial Board of *AES Technical Reviews International Journal* (*Part A: International Journal of Nano and Advanced Engineering Materials (IJNAEM), Part B: International Journal of Advances in Mechanics and Applications of Industrial Materials (IJAMAIM), Part C: International Journal of Advances and Trends in Engineering Materials and their Applications (IJATEMA), Part D: International Journal of Reliability and Safety of Engineering Systems and Structures (IJRSESS)*), the Editorial Advisory Board of *The Open Civil Engineering Journal/The Open Textile Journal/The Open Conference Proceeding Journal/The Open Physics Journal* (formerly *The Open Mechanics Journal*), the Editorial Board of *Advances in Theoretical and Applied Mechanics, Chemical Engineering and Process Techniques, International Scholarly Research Notices (Mechanical Engineering), Journal of Applied Mathematics*, the editorial board of *Strength, Fracture and Complexity*, An International Journal, and the Editor-in-Chief of *The Open Mechanical Engineering Journal* and *International Journal of Metallurgical & Materials Engineering*. His primary research interests are in the areas of mesomechanics of material systems and structures, electromagnetic fracture and damage mechanics, dynamics and cryomechanics of advanced composite materials/structural alloys, and reliability and durability of micro-/nanocomponents and devices.

# Preface

The science of electromagneto-mechanics, which is concerned with the interaction of electromagnetic fields and deformation in material systems and structures, has developed because of the possibility of its practical applications in various fields such as electronic and electromechanical devices. As the area of science and technology expands, it becomes important that newly acquired knowledge and expertise are communicated effectively to those who can gain most by applying them in practice. This book covers a very wide and varied range of subject areas that fall under its subject and all aspects (theoretical, experimental, computational studies, and/or industrial applications) of electromagneto-mechanics from state-of-the-art fundamental research to applied research and applications in emerging technologies.

YASUHIDE SHINDO
*Sendai, Japan*
*September, 2014*

# Acknowledgments

I am indebted to many authors whose writings are classics in the field of electromagneto-mechanics. It is also a pleasure to acknowledge the help received from my students and colleagues. Special thanks go to Professor Fumio Narita of Tohoku University, who read the entire manuscript and gave me many valuable suggestions for improvement. Finally, I would like to thank the publisher John Wiley & Sons for their continuous support for this project.

# Contents

# 1

# Introduction

The electromagneto-mechanics of material systems and structures has been developing rapidly with extensive applications in, for example, electronic industry, magnetic fusion engineering, superconducting devices, and smart materials and microelectromechanical systems (MEMS). Researchers in this interdisciplinary field are with diverse background and motivation. This book reflects a cross section of recent activities in the electromagneto-mechanics of conducting materials, dielectric materials, piezoelectric materials and devices, ferromagnetic materials, magnetostrictive material systems, and so on.

Chapter 2 deals with the magneto-mechanics of conducting material systems and structures. Here, the theory of dynamic magnetoelasticity is presented. Vibrations and waves of conducting plates are then considered, and the effect of the magnetic field on the flexural waves is examined. The theory is also applied to various problems for cracked conducting plates, and the influence of the magnetic field on the dynamic singular stresses is displayed graphically and discussed. In addition, the results for the cracked plates under large electric current and strong magnetic field are presented, and the effect of the electromagnetic force on the mechanical behavior is shown.

Chapter 3 provides the electromechanical interactions of dielectric/ferroelectric material systems and structures. In Part 3.1, we present the theory of dielectrics. Basic equations of electroelasticity are given. Applications are then made to static electroelastic crack mechanics, electroelastic vibrations and waves, and dynamic electroelastic crack mechanics of dielectric materials. Part 3.2 is devoted to the discussion of linear and nonlinear piezoelectricity. For a literature on this topic, we refer readers to Tiersten [1]. Piezomechanics and basic equations are presented. Theory is then applied to various problems, including bending behavior, electromechanical field concentrations, and cryogenic electromechanical response. Experimental data are also shown to validate the theoretical model. Furthermore, the theoretical and experimental results on the electric field dependence of fracture and fatigue of piezoelectric material systems are presented.

In Chapter 4, we deal with the magneto-mechanics of ferromagnetic material systems and structures. Part 4.1 presents the theory and test of ferromagnetics. Reference on this topic may be made to Brown [2]. Basic equations of magnetoelasticity are developed. Theory is then applied to various problems, including magnetoelastic instability, magnetoelastic vibrations, and waves of soft ferromagnetic and magnetically saturated materials under magnetic

*Electromagneto-Mechanics of Material Systems and Structures*, First Edition. Yasuhide Shindo.

fields, and some experiments are performed to validate the theoretical predictions. The magnetoelastic analysis and experimental evidence are also presented for cracked plates under bending, and the effect of magnetic fields on the moment intensity factor is shown. Moreover, the tensile fracture and fatigue of soft ferromagnetic materials under magnetic fields are dedicated. Part 4.2 is concerned with a discussion of magnetostriction. Works on the subject are found to be in du Tremolet de Lacheisserie [3]. Basic equations of magnetostriction are given. Theoretical and experimental treatments of the nonlinear magneto-mechanical response in magnetostrictive material systems are then presented. Here, the material systems consist of the magnetostrictive and elastic layers, and later, we consider the magnetostrictive layer bonded to the piezoelectric layer. In addition, the piezomagnetoelectric effect of particle-reinforced composites is discussed.

There are extensive literatures on this subject. Some books are listed as follows. That is, Moon [4] organized the existing literatures on magneto-solid mechanics and gave a presentation of the basic principles and some useful method of analysis. Parton and Kudryavtsev [5] analyzed the behavior of piezoelectric materials and considered strength and failure problems for piezoelectric and electrically conducting materials. In addition, Eringen and Maugin [6, 7] presented a unified approach to the nonlinear continuum theory of deformable and fluent materials subjected to electromagnetic and thermal loads. Also, there are the following conference proceedings books of IUTAM symposium: Maugin [8], Yamamoto and Miya [9], and Hsieh [10], and of other mini-symposiums: Lee et al. [11], Yang and Maugin [12], and Shindo [13]. Moreover, the following monographs present a good discussion of this subject: Paria [14], Parkus [15, 16], Alblas [17], Moon [18], Hutter and van de Ven [19], Pao [20], Hsieh [21], Ambartsumian [22], and the set of chapters edited by Parkus [23]. In the above-listed literatures, references to other papers can be found.

## References

[1] H. F. Tiersten, *Linear Piezoelectric Plate Vibration*, Plenum Press, New York, 1969.
[2] W. F. Brown, Jr., *Magnetoelastic Interactions*, Springer-Verlag, Berlin, 1966.
[3] E. du Tremolet de Lacheisserie, *Magnetostriction: Theory and Applications of Magnetoelasticity*, CRC Press, Boca Raton, FL, 1993.
[4] F. C. Moon, *Magneto-Solid Mechanics*, John Wiley & Sons, Inc., New York, 1984.
[5] V. Z. Parton and B. A. Kudryavtsev, *Electromagnetoelasticity*, Gordon and Breach Science Publishers, New York, 1988.
[6] A. C. Eringen and G. A. Maugin, *Electrodynamics of Continua I*, Springer-Verlag, New York, 1989.
[7] A. C. Eringen and G. A. Maugin, *Electrodynamics of Continua II*, Springer-Verlag, New York, 1990.
[8] G. A. Maugin (ed.), *Proceedings of the IUTAM/IUPAP Symposium on the Mechanical Behavior of Electromagnetic Solid Continua*, North-Holland, Amsterdam, 1984.
[9] Y. Yamamoto and K. Miya (eds.), *Proceedings of the IUTAM Symposium on Electromagnetomechanical Interactions in Deformable Solids and Structures*, North-Holland, Amsterdam, 1987.
[10] R. K. T. Hsieh (ed.), *Proceedings of the IUTAM Symposium on Mechanical Modeling of New Electromagnetic Materials*, Elsevier, Amsterdam, 1990.
[11] J. S. Lee, G. A. Maugin and Y. Shindo (eds.), *Mechanics of Electromagnetic Materials and Structures*, AMD-Vol. 161, MD-Vol. 42, ASME, New York, 1993.
[12] J. S. Yang and G. A. Maugin (eds.), *Mechanics of Electromagnetic Materials and Structures*, IOS Press, Amsterdam, 2000.
[13] Y. Shindo (ed.), *Mechanics of Electromagnetic Material Systems and Structures*, WIT Press, Southampton, 2003.
[14] G. Paria, "Magneto-elasticity and magneto-thermo-elasticity," *Adv. Appl. Mech.* **10**, 73 (1967).