Preface to the Second Edition

The original version of this book, *EMATs for Science and Industry: Noncontacting Ultrasonic Measurements*, was published by Kluwer Academic Publishers in 2003. The main theme of the book remains unchanged, but this second edition contains new research products that have emerged since then and that we were unaware of when the original book was prepared.

The thematic chapters and sections are rearranged to accommodate new entries of guided torsional waves (Sects. 3.4 and 14.3), point-focusing EMATs (Sects. 3.10 and 14.4), antenna transmission technique (Sects. 3.13 and 8.9), point-defect dynamics in aluminum (Sect. 7.3), high-temperature measurement of elastic constants (Sects. 8.5 and 8.9), resonant ultrasound microscopy (Chap. 9), and EMAR-based nonlinear acoustic measurements (Chap. 10). We created Chap. 18 to summarize the field applications of EMATs. It is enriched by the addition of monumental works, corrosion detection of heat exchanger tube, and in-process weld inspection. Chapter 2 becomes more comprehensive for describing coupling mechanisms on EMAT phenomena. Errors in equations have been corrected: Eqs. (2.51), (2.60), (13.2), (13.5), and (13.8) in the original version.

EMATs of low transduction efficiency have been thought to be useful only when the users need their unique advantages, that is, the noncontact nature and the ability to transmit and receive elastic wave modes that are otherwise difficult. However, it is demonstrated, for instance, that the point-focusing EMAT can detect stress-corrosion cracks around the weld of stainless steel plates and showed a great latent potential for flaw detection. We hope that this publication triggers such new ideas of ultrasonic measurements and contributes to the development in materials science research and nondestructive evaluation of industrial materials.

In preparing this book, we have benefited from the advice and encouragement of many colleagues. G. Petersen (Ritec Inc.) contributed Sect. 4.3 on impedance matching. Particular gratitude is due to G. Alers (Sonic Sensors of EMAT Ultrasonics, Inc.) for his advice and support with Chap. 18. P. Nagy (University of Cincinnati) provided us with valuable discussions on the EMAT mechanisms in Chap. 2. Students

fabricated the EMATs in our laboratory. Their efforts in modeling and experiments resulted in finding new phenomena and suggestions for next directions.

In March 2011, we heard with deepest regret of the passing of R. Bruce Thompson. He pioneered and guided the EMAT research over decades in developing the theoretical model and practical applications. His research work that appeared in the 1970s is the milestone through the history of EMATs development. We dedicate this book to Bruce with many thanks and as a tribute to his great accomplishment.

Toyonaka, Osaka Masahiko Hirao
Spring 2016 Hirotsugu Ogi

Preface to the First Edition

A man with hammer sees everything as a nail.

Against this lesson, the authors of this book have kept hitting things with *electromagnetic acoustic transducers* (EMATs) for the purposes of studying the sound they made. This book comprises the physical principles of EMATs and the applications of scientific and industrial ultrasonic measurements on materials. The objects are summarized and systematized mainly from the authors' own research results in Osaka University. The choice of subjects is admittedly arbitrary and strongly influenced by the authors' own interests and views.

The text is arranged in four parts. Part I is intended to be a self-contained description of the basic elements of coupling mechanism along with practical designing of EMATs for various purposes. There are several implementations to compensate for the low transfer efficiency of the EMATs. Useful tips to make an EMAT are also presented. Part II describes the principle of EMAR, which makes the most of contactless nature of EMATs and is the most successful amplification mechanism for precise velocity and attenuation measurements. In Part III, EMAR is applied to studying the physical acoustics. New measurements emerged on three major subjects; *in situ* monitoring of dislocation behavior, determination of anisotropic elastic constants, and acoustic nonlinearity evolution. Part IV deals with a variety of individual topics encountered in industrial applications, for which the EMATs are believed to the best solutions.

Our study on EMATs started more than ten years ago. The 5th International Symposium on Nondestructive Characterization of Materials took place in May 1991, at Karuizawa, Japan. One afternoon during the Symposium, H. Fukuoka, the late C. M. Fortunko, G. L. Petersen, T. Miya, T. Yamasaki, and one of the authors (M.H.) got together and discussed the possibility of mechanizing the resonant—EMAT concept. We were trying to push forward the project of measuring the acoustoelastic response in thin metal sheets, for which extremely high-frequency resolution was required. Among several potential approaches, the pulsed CW excitation and superheterodyne detection on gated reverberation signals seemed promising. But we were not sure whether it was achievable with EMATs. In October, M.H. flew to Providence, Rhode Islands, with a bulk-wave EMAT built by the other author (H.O.), who was then a graduate student. Japan-made EMAT was connected to US-made instrument for the first time and the combination produced exactly what we wanted, the high-Q resonance spectrum with metal sheets.

This was the birth of *electromagnetic acoustic resonance* (EMAR) of the latest generation. The system was found well applicable not only to acoustoelastic stress measurements, but also to many other nondestructive evaluation issues, including the determination of attenuation in solids. Noncontact measurement with high enough signal intensity was striking. Basic preconditions of theoretical approaches were realized by eliminating artifacts caused by the contact transducers. EMAR thus illuminated antiquated theories, which were accepted to be of little use or limited to qualitative interpretation of observations. It also uncovered interesting phenomena. Continuous monitoring of attenuation and acoustic nonlinearity resulted in the detection of ongoing microstructure evolutions in deforming or fatiguing metals. Our aim of writing this is to share the knowledge of and the results obtained with EMATs with students, researchers, and practitioners who had no chance to know the value. We hope that this book provides practical answers to the needs of ultrasonic measurements and direction to open a novel methodology.

We wish to acknowledge the influence of H. Ledbetter, who over a long period taught us physical metallurgy and elastic-constant theories, which formed the background of the ultrasonic researches described herein. Furthermore, he has taken a critical reading of the whole manuscript through intensive examination and corrections. We sincerely appreciate his attention, advice, and encouragement.

Many friends and colleagues helped us with the research and this book in their ways. Of special note are the stimulating discussions with the late C. M. Fortunko, G. A. Alers, and W. Johnson on EMATs and ultrasonic measurements in general. T. Ohtani collaborated with us by designing printed coils as well as by developing measurements to sense metal's fatigue and creep damages. T. Ichitsubo extended EMAR measurements to materials science field and low-temperature solid-state physics. T. Yamasaki and K. Yaegawa deserve our many thanks. We acknowledge the invaluable support of Ritec Inc. (B. B. Chick, G. L. Petersen, M. J. McKenna) and Sonix K.K. (T. Miya). From the very beginning till now, they have provided us with the state-of-the-art instruments, which have done much to shape our ideas on ultrasonic researches. G. L. Petersen wrote Section 3.3 on impedance matching with EMATs. K. Fujisawa and R. Murayama, when they were at Sumitomo Metal Indust., introduced the magnetostrictive coupling to us during the joint work to develop online texture monitoring system on steel sheets. That was our first contact with EMATs. W. Johnson and K. Fujisawa gave criticisms by reading portions of the manuscript. Many students contributed to the EMAT studies through painstaking work in calculations and experiments; they are S. Aoki, T. Hamaguchi, T. Honda,

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Lastly, we wish to thank our mentor, H. Fukuoka, for his encouragement during the preparation and his foresight that the EMATs should further develop ultrasonic measurements. He suggested that we pursue acoustoelastic programs with EMATs. They were the toughest subjects, but when solved, other subjects of ultrasonic measurements became easier tasks.

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