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Ultrasonic Nondestructive Evaluation Systems

Models and Measurements

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Dedications

To my parents, Ida Clara (Streithorst) Schmerr and Lester William Schmerr Sr., and to my wife Mary Jo (Freiburger) Schmerr

Lester W. Schmerr Jr.

To my mother, Byung-Nam Kim, and to my wife, Hea Young Jung

Sung-Jin Song

Preface

This book deals with ultrasonic nondestructive evaluation (NDE) inspections where high frequency waves are used to locate and characterize dangerous flaws (such as cracks) in materials. Ultrasonic NDE flaw inspections involve a very complex combination of electrical, electromechanical, and acoustic/elastic components so that it is important to understand the behavior of those components and their interactions in order to make quantitative flaw measurements. It will be shown that through the use of models and measurements it is now possible to characterize all the elements of an ultrasonic NDE flaw inspection system. Those elements include the pulser/receiver, the cabling, the transducers, and the wave propagation and scattering processes present in an ultrasonic NDE flaw measurement. It will also be demonstrated how to combine models and measurements of those elements to form ultrasonic measurement models which can simulate the flaw signals seen in ultrasonic NDE tests. This comprehensive modeling and measurement capability is described for the first time in this book.

There are important engineering applications of this new technology. For example, these ultrasonic models and measurements can be used to design new ultrasonic inspections as well as optimize existing ones. This technology can also help one to extract information on the nature of the flaw present from the measured ultrasonic flaw signals that can then be used to evaluate the safety and reliability of the material being inspected.

The topics covered in this book include Fourier analysis, linear system theory, and wave propagation and scattering theory for fluids and solids. A series of Appendices provide some background materials for all these topics. Additional background information in these areas can be found in *Fundamentals of Ultrasonic Nondestructive Evaluation – A Modeling Approach* by L. W. Schmerr Jr. This book will also provide many details of the fundamentals of the ultrasonic measurement process but the primary purpose here is to show how the elements of an ultrasonic measurement system combine to generate a measured signal received from a flaw in a material and to give models and measurements that make it practical to simulate those measured flaw signals. In addition to giving the equations and models that govern the behavior of an ultrasonic system we also develop some simple but powerful MATLAB functions and scripts. Those functions/scripts can be used by the reader to conduct simulated inspections and to quickly learn how to implement this modeling technology. The validity of the models discussed is also demonstrated by comparing them to experiments.

There are two parts of this book that warrant special notice. First, a recently developed pulse-echo method for measuring the sensitivity of an ultrasonic transducer is given in Chapter 6. This method makes the experimental characterization of transducers much easier than previous methods. Since transducer characterization is an important part of the series of measurements needed to characterize completely all the components an ultrasonic measurement system, having this simple method for calculating sensitivity also makes that entire chain of measurements more practical. Second, in Chapter 9 we give a complete description of Gaussian beam theory and its use for simulating the wave fields generated by ultrasonic transducers in the form of a multi-Gaussian beam model. Although there are other methods for calculating these wave fields, multi-Gaussian beam models are generally the most effective ultrasonic beam models available. Gaussian beams have been described in other application areas such as Laser science and Geophysics, but the underlying theory as it relates to NDE problems has not been previously given in a complete and unified manner. Chapter 9, therefore, provides a detailed discussion of Gaussian beams as used for modeling sound beams in fluids and isotropic, homogeneous elastic solids. Because the general treatment in Chapter 9 necessarily leads to a lengthy and detailed description of Gaussian beam theory, Appendix F describes the propagation and transmission/reflection of circularly symmetric Gaussian beams along a single direction, a simple case where the properties of these beams can be more clearly illustrated and explained.

This book is an outgrowth of over thirty years of ultrasonic NDE modeling research by the two authors, their colleagues from around the world, and many students. It is designed to communicate that research in an organized fashion and to serve as the foundation for solving many important ultrasonic NDE problems. However, it is also our vision that this modeling technology is not just for the "modelers". We believe that modeling can affect the NDE community at all levels. Thus, the book was developed as part of a workshop series sponsored by the World Federation of NDE Centers (www.wfndec.org). One purpose of that series is to "teach the teacher", that is to provide materials to those with a responsibility for supervising and educating others in the NDE field so that they in turn could communicate the materials and resulting knowledge to others. This book is written at an advanced undergraduate or graduate education level, but by combining the concepts presented here with the simulation capabilities that the MATLAB functions provide one can use or deliver this material at a number of levels. We hope that the reader will enjoy learning about how ultrasonic NDE systems work as much as we have and will pass that learning on to others. We have placed exercises at the end of some of the Chapters and Appendices (most of them MATLAB-based) to help in that learning process.

We would especially like to thank Prof. Alexander Sedov and Drs. Hak-Joon Kim, Ana Lopez-Sanchez, Ruiju Huang, and Changjiu Dang for both their contributions to the research that has helped make this book possible and for their assistance in its preparation.

L.W. Schmerr
S.J. Song

Contents

1 Introduction

1.1 Prologue

In the following Chapters we will describe in detail models that can be used to characterize all the elements of an ultrasonic nondestructive evaluation (NDE) flaw measurement system. We will also discuss the measurements needed to obtain the system parameters that appear in the models. These models can be used to optimize existing inspections, design new inspections, and analyze inspection results. This technology can also be a major cost-saving tool for industry if the models are used to replace expensive tests and sample fabrications. For this to occur, it must be clear that the models are accurate and reliable. We hope to provide sufficient information on current ultrasonic NDE modeling efforts so that the reader can better judge for himself/herself the maturity of this field.

Many aspects of modeling ultrasonic NDE systems require a background in linear system theory and wave propagation and scattering theory. We will provide some of that background in the Appendices and later Chapters but in many cases we will state results without proof and point the reader to other sources. One source in particular that will be referred to frequently is the book *Fundamentals of Ultrasonic Nondestructive Evaluation – A Modeling Approach* by L.W. Schmerr Jr. which is listed as a reference at the end of this Chapter. In subsequent discussions that source will be referred to as the reference [Fundamentals].

In this Chapter we will provide an overview of the models and methods that will be discussed in later Chapters, using the flaw measurement setup of Fig. 1.1 as an example. We will highlight the major results that allow us to model all the components of Fig.1.1 and ultimately obtain an explicit model of the entire measurement system. Although most of our discussions will refer to the immersion system of Fig. 1.1, the models are also applicable to other NDE setups that involve angle beam and contact transducers. Some angle beam inspection applications of the models, for example, are described in Chapter 13.

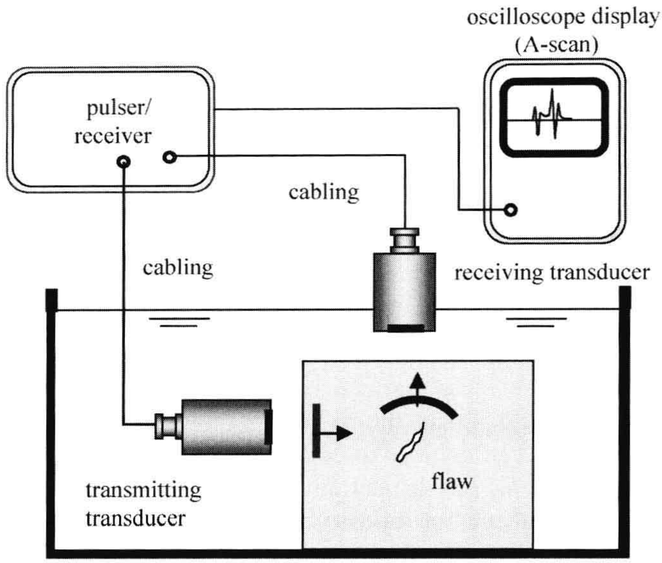

Fig. 1.1. The components of an ultrasonic flaw measurement system.

Throughout this book we will only model inspection systems that use bulk waves. Appendix E gives a brief introduction to the properties of other types of waves such as surface (Rayleigh) waves and guided waves but models of inspections with those wave types require transducer models and wave propagation and scattering models that are not treated here.

1.2 Ultrasonic System Modeling – An Overview

An ultrasonic measurement system involves the generation, propagation, and reception of short transient signals. In the electrical elements of the system shown in Fig. 1.1 such as the pulser/receiver and cabling, these signals are electrical pulses. In the acoustic/elastic parts of the system, the signals are short time duration acoustical pulses traveling in either fluids or solids. The ultrasonic transducers are "mixed" devices that transform electrical pulses into acoustic pulses, and vice-versa. In modeling ultrasonic systems it is convenient not to deal with these transient signals directly but to work instead with their spectral (frequency domain) components.

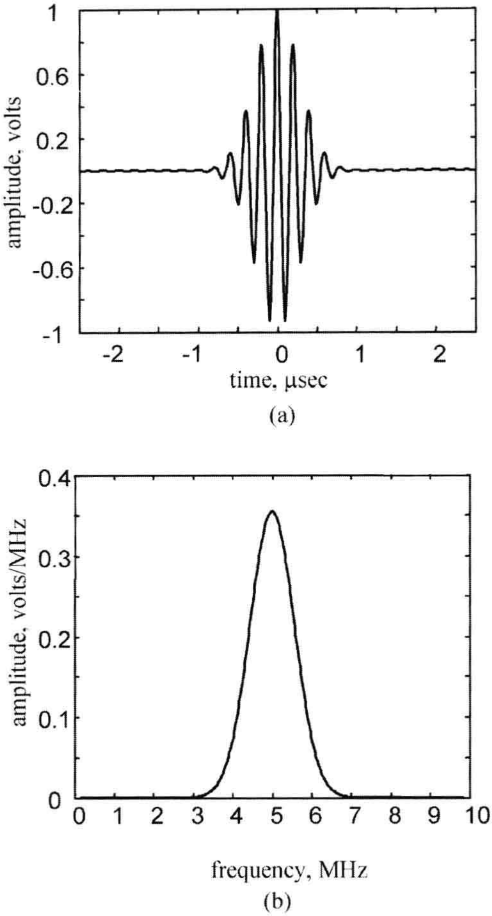

Fig. 1.2. (a) A voltage versus time trace and **(b)** the magnitude of its frequency domain spectrum (for positive frequencies).

Thus, Fourier analysis becomes an essential part of any discussion of ultrasonic system modeling. Figure 1.2, for example, shows a simulated transient voltage versus time signal that might be measured in an ultrasonic NDE system and its corresponding spectral amplitude. It can be seen that the pulse in Fig. 1.2 is very short (typically on a microsecond scale) and the corresponding frequencies in the pulse spectrum are in the 10^6 Hz (MHz) range. These values are similar to the pulses and spectra one often finds in NDE tests. Appendix A gives a brief introduction to Fourier

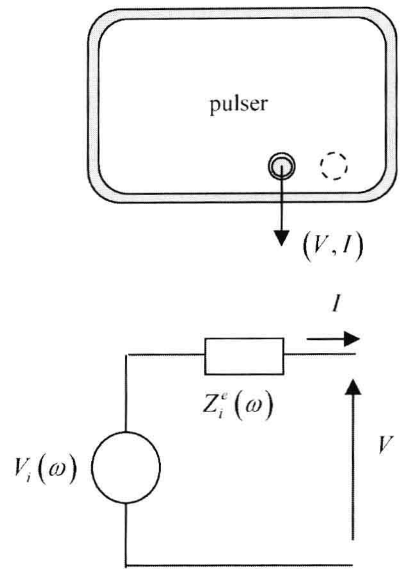

Fig. 1.3. An ultrasonic pulser and an equivalent circuit model as a voltage source and electrical impedance.

transforms, Fast Fourier transforms and related concepts that form some of the fundamental foundations for transforming time signals into frequency domain signals and vice-versa.

Chapter 2 discusses the modeling of the pulser section of a pulser/receiver and the basic characteristics of the signals generated by the pulser. The pulser is an active electrical network, i.e. it contains a driving energy source as well as complex circuits that shape the output electrical pulse. If the pulser acts as a linear device, then it can be replaced by a very simple equivalent model (in the frequency domain) consisting of a voltage source, $V_i(\omega)$, and impedance, $Z_i^e(\omega)$, both of which are complex functions of the circular frequency, ω, as shown in Fig. 1.3. This representation is possible because of a fundamental theorem of electrical circuits called Thévenin's Theorem. Appendix B gives a brief proof of Thévenin's theorem and discusses the concept of impedance. It is demonstrated in Chapter 2 that one can experimentally determine the voltage source and impedance terms shown in Fig. 1.3 by performing a set of electrical voltage measurements on the pulser under different loading conditions.