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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](http://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

<b>1 Introduction.....</b>	<b>1</b>
1.1 Prologue.....	1
1.2 Ultrasonic System Modeling – An Overview.....	2
1.3 Some Remarks on Notation.....	19
1.4 Organization of the Book.....	19
1.5 Reference.....	20
1.6 Suggested Reading.....	20
<b>2 The Pulser.....</b>	<b>21</b>
2.1 Characteristics of a Pulser.....	21
2.2 Measurement of the Circuit Parameters of a Pulser.....	24
2.3 Pulser Models.....	31
2.4 References.....	34
2.5 Exercises.....	34
<b>3 The Cabling.....</b>	<b>35</b>
3.1 Cable Modeling.....	35
3.2 Measurement of the Cabling Transfer Matrix.....	41
3.3 References.....	44
3.4 Exercises.....	44
<b>4 Transmitting Transducer and the Sound Generation Process.....</b>	<b>47</b>
4.1 Transducer Modeling.....	47
4.2 Transducer Acoustic Radiation Impedance.....	54
4.3 Transducer Impedance and Sensitivity.....	58
4.4 The Sound Generation Process.....	60
4.5 References.....	63
4.6 Exercises.....	63
<b>5 The Acoustic/Elastic Transfer Function and the Sound Reception Process.....</b>	<b>67</b>
5.1 Wave Processes and Sound Reception.....	67
5.2 The Blocked Force.....	69

5.3 The Acoustic/Elastic Transfer Function .....	71
5.4 The Acoustic Sources and Transducer on Reception .....	77
5.5 The Cable and the Receiver in the Reception Process.....	83
5.6 A Complete Reception Process Model .....	88
5.7 References .....	93
5.8 Exercises.....	93
<b>6 Transducer Characterization .....</b>	<b>95</b>
6.1 Transducer Electrical Impedance .....	95
6.2 Transducer Sensitivity .....	98
6.3 Transducer Effective Radius and Focal Length.....	108
6.4 References .....	113
6.5 Exercises.....	114
<b>7 The System Function and Measurement System Models.....</b>	<b>115</b>
7.1 Direct Measurement of the System Function .....	115
7.2 System Efficiency Factor.....	118
7.3 Complete Measurement System Modeling.....	120
7.4 References .....	125
7.5 Exercises.....	125
<b>8 Transducer Sound Radiation.....</b>	<b>127</b>
8.1 An Immersion Transducer as a Baffled Source .....	127
8.2 An Angular Plane Wave Spectrum Model .....	130
8.3 A Rayleigh-Sommerfeld Integral Transducer Model .....	134
8.4 On-Axis Behavior of a Planar Circular Piston Transducer.....	137
8.5 The Paraxial Approximation.....	139
8.6 Far field On-Axis and Off-Axis Behavior .....	143
8.7 A Spherically Focused Piston Transducer .....	146
8.8 Wave Field in the Plane at the Geometrical Focus .....	152
8.9 Radiation of a Focused Transducer through an Interface .....	153
8.10 Sound Beam in a Solid Generated by a Contact Transducer .....	154
8.11 Angle Beam Shear Wave Transducer Model .....	159
8.12 Transducer Beam Radiation through Interfaces .....	159
8.13 Acoustic/Elastic Transfer Function – Focused Transducer .....	164
8.14 Acoustic/Elastic Transfer Function – Rectangular Transducer ..	171
8.15 References .....	174
8.16 Exercises.....	174
<b>9 Gaussian Beam Theory and Transducer Modeling.....</b>	<b>179</b>
9.1 The Paraxial Wave Equation and Gaussian Beams in a Fluid.....	180
9.2 The Paraxial Wave Equation and Gaussian Beams in a Solid.....	194

9.3 Transmission/Reflection of a Gaussian Beam at an Interface .....	196
9.4 Gaussian Beams and ABCD Matrices .....	212
9.5 Multi-Gaussian Transducer Beam Modeling.....	221
9.6 References .....	230
9.7 Exercises .....	231
<b>10 Flaw Scattering .....</b>	<b>235</b>
10.1 The Far-Field Scattering Amplitude .....	235
10.2 The Kirchhoff Approximation for Volumetric Flaws.....	241
10.3 The Leading Edge Response of Volumetric Flaws .....	247
10.4 The Kirchhoff Approximation for Cracks .....	251
10.5 Validity of the Kirchhoff Approximation .....	258
10.6 The Kirchhoff Approximation for Side-drilled Holes .....	268
10.7 The Born Approximation.....	277
10.8 Separation of Variables Solutions .....	286
10.9 Other Scattering Models and Methods .....	293
10.10 References .....	296
10.11 Exercises .....	298
<b>11 Ultrasonic Measurement Models.....</b>	<b>301</b>
11.1 Reciprocity-based Measurement Model .....	301
11.2 The Thompson-Gray Measurement Model.....	314
11.3 A Measurement Model for Cylindrical Reflectors .....	316
11.4 References .....	319
11.5 Exercises .....	320
<b>12 Ultrasonic Measurement Modeling with MATLAB.....</b>	<b>323</b>
12.1 A Summary of the Measurement Models .....	323
12.2 The Multi-Gaussian Beam Model .....	327
12.3 Measurement Model Input Parameters .....	331
12.4 A Multi-Gaussian Beam Model in MATLAB .....	337
12.5 Ultrasonic Attenuation in the Measurement Model.....	348
12.6 The System Function .....	350
12.7 Flaw Scattering Models .....	353
12.8 The Thompson-Gray Measurement Model.....	357
12.9 A Large Flaw Measurement Model.....	373
12.10 A Measurement Model for Cylindrical Reflectors .....	378
12.11 References .....	387
<b>13 Applications of Ultrasonic Modeling.....</b>	<b>389</b>
13.1 Obtaining Flaw Scattering Amplitudes Experimentally .....	389
13.2 Distance-Amplitude-Correction Transfer Curves.....	393

13.3 Angle Beam Inspection Models and Applications .....	404
13.4 Model-Assisted Flaw Identification .....	425
13.5 Model-Assisted Flaw Sizing.....	433
13.6 References .....	437
<b>A Fourier Transforms and the Delta Function .....</b>	<b>439</b>
A.1 The Fourier Transform and Its Inverse .....	439
A.2 The Discrete Fourier Transform .....	447
A.3 The Delta Function .....	452
A.4 References.....	454
A.5 Exercises .....	455
<b>B Impedance Concepts and Equivalent Circuits .....</b>	<b>459</b>
B.1 Impedance.....	459
B.2 Thévenin's Theorem .....	463
B.3 Measurement of Equivalent Sources and Impedances.....	468
B.4 References.....	470
B.5 Exercises .....	470
<b>C Linear System Fundamentals .....</b>	<b>473</b>
C.1 Two Port Systems .....	473
C.2 Linear Time-Shift Invariant (LTI) Systems .....	480
C.3 References.....	486
C.4 Exercises .....	486
<b>D Wave Propagation Fundamentals .....</b>	<b>491</b>
D.1 Waves in a Fluid .....	491
D.2 Plane Waves in a Fluid .....	493
D.3 Waves in an Isotropic Elastic Solid .....	496
D.4 Plane Waves in an Isotropic Elastic Solid .....	498
D.5 Reflection/Refraction of Plane Waves – Normal Incidence .....	504
D.6 Reflection/Refraction of Plane Waves – Oblique Incidence .....	507
D.7 Spherical Waves .....	522
D.8 Ultrasonic Attenuation.....	525
D.9 References.....	529
D.10 Exercises .....	529
<b>E Waves Used in Nondestructive Evaluation .....</b>	<b>535</b>
E.1 Shear Waves.....	535
E.2 Rayleigh Waves .....	537
E.3 Plate (Lamb) Waves.....	539
E.4 References .....	542

---

<b>F Gaussian Beam Fundamentals .....</b>	<b>543</b>
F.1 Gaussian Beams and the Paraxial Wave Equation .....	543
F.2 Quasi-Plane Wave Conditions and the Paraxial Approximation..	549
F.3 Transmission/Reflection of a Gaussian Beam.....	552
F.4 Gaussian Beams at Multiple Interfaces and ABCD Matrices .....	558
F.5 Multi-Gaussian Beam Modeling .....	568
F.6 References .....	570
F.7 Exercises.....	570
 <b>G MATLAB Functions and Scripts .....</b>	 <b>575</b>
G.1 Fourier Analysis Functions.....	575
G.2 Setup Functions .....	578
G.3 Ultrasonic Beam Modeling Functions .....	578
G.4 Flaw Scattering Functions .....	580
G.5 Ultrasonic Measurement Modeling Functions.....	581
G.6 Miscellaneous Functions.....	582
G.7 MATLAB Script Examples .....	582
G.8 Code Listings of Some Supporting Functions .....	584
 <b>Index.....</b>	 <b>599</b>

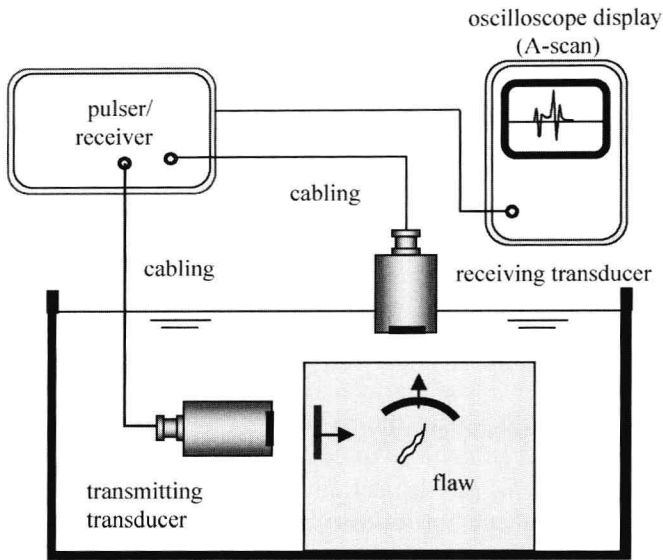
# 1 Introduction

## 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.

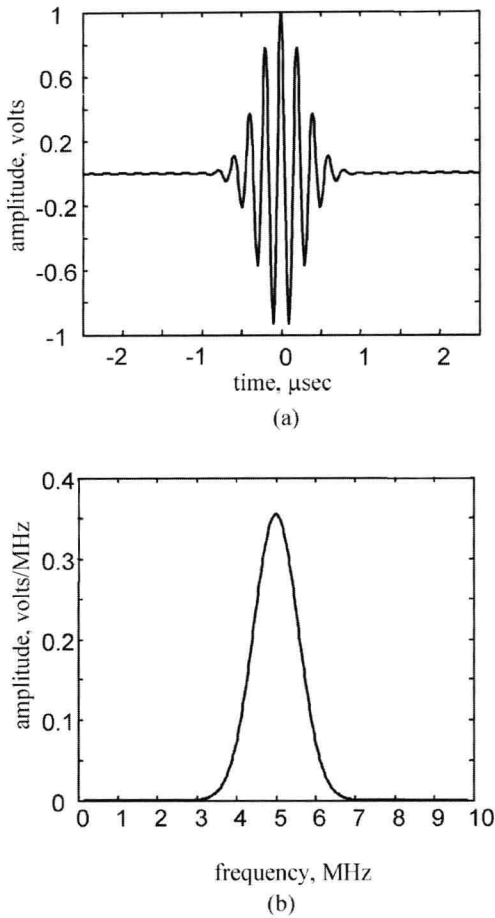


**Fig. 1.1.** The components of an ultrasonic flaw measurement system.

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

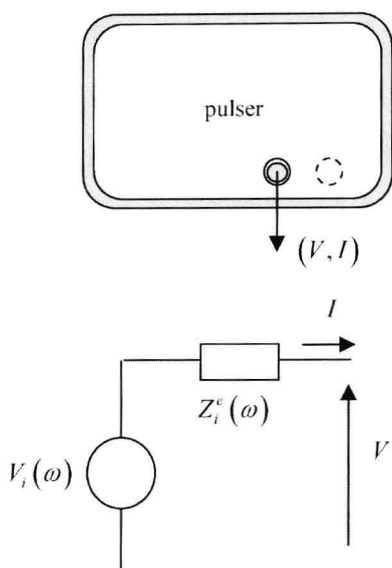
An ultrasonic measurement system involves the generation, propagation, and reception of short transient signals. In the electrical elements of the system shown in Fig. 1.1 such as the pulser/receiver and cabling, these signals are electrical pulses. In the acoustic/elastic parts of the system, the signals are short time duration acoustical pulses traveling in either fluids or solids. The ultrasonic transducers are “mixed” devices that transform electrical pulses into acoustical 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,  $\omega$ , 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.