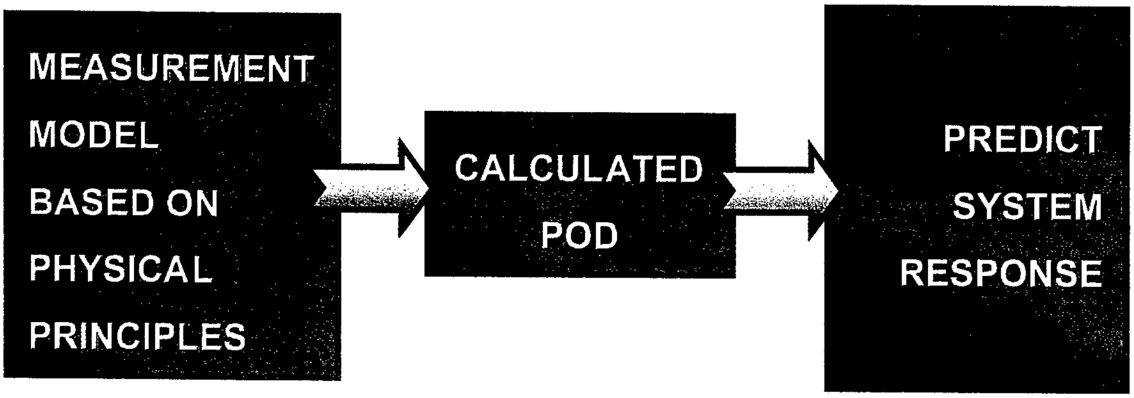
Overview of

Mathematical Modeling in Nondestructive Evaluation (NDE)

NTIAC-TA-02-01



MEASUREMENT MODEL BASED ON PHYSICAL PRINCIPLES

CALCULATED POD

PREDICT SYSTEM RESPONSE

Nondestructive Testing Information Analysis Center
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September 2002

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OVERVIEW OF

Mathematical Modeling In Nondestructive Evaluation (NDE)

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NTIAC

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PREFACE

This Overview was prepared for NTIAC by Dr. John C. Aldrin of Computational Tools, 6797 Roanoake Ct. Gurnee, IL 60031. Dr. Aldrin is also a Visiting Scientist, Air Force Research Laboratory and this work was prepared as part of an ongoing effort under the AFOSR task, "Computational Methods in Nondestructive Evaluation." Preparation of this report was supported by the Air Force Research Laboratory – Materials and Manufacturing Directorate.

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TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

1.1 Background

Nondestructive evaluation (NDE) is used to detect and characterize anomalies in materials and structures in order to ensure reliability and extend the service life of the component. Over the years, nondestructive evaluation (NDE) has contributed significantly to material process control, part fabrication, and economic service life management programs of industry and government.

A block diagram of a general NDE measurement technique is shown in Figure 1.1. NDE techniques have typically been developed using heuristic approaches from empirical data. Thus, an engineer would design the test setup and procedure through experience with the measurement equipment and test samples. This experience would also be used to design a procedure to interpret the raw data resulting in a measure value for the sample or providing features for classification of the sample condition.

Although empirical approaches have been successful in the past, existing trends have made the development of new inspection techniques more difficult. Such trends include an increase in the use of advanced materials, aging aircraft and infrastructure requiring the testing of component not designed for inspection, the need for flaw characterization, the goal to reduce inspector variability through automation, and greater cost scrutiny. Given this environment, to achieve the goal of improving existing nondestructive techniques and aiding in the development of new techniques, a better understanding of the physics of NDE measurement techniques is needed.

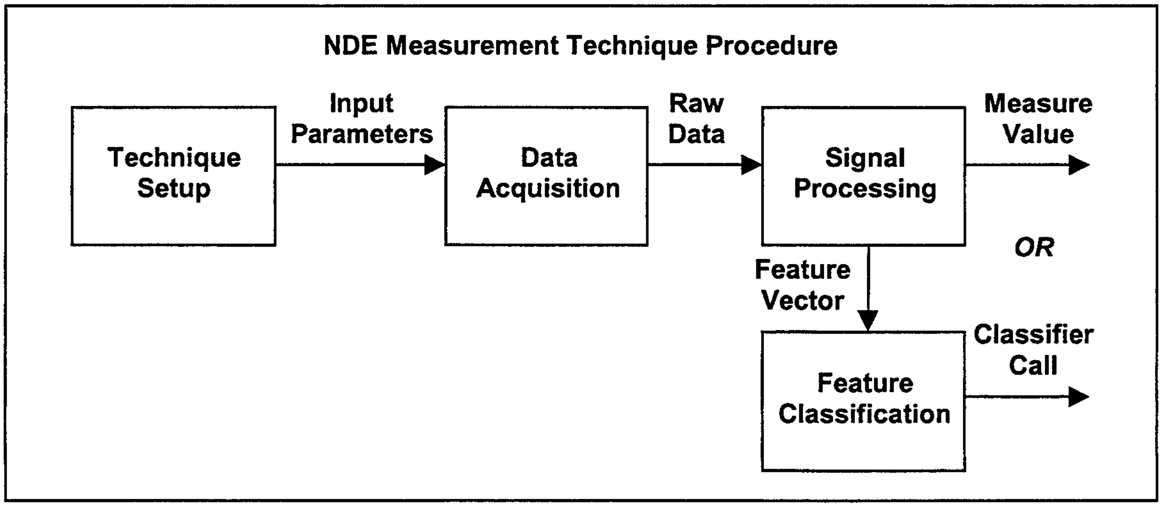

Figure 1.1. Components of NDE measurement technique procedure.

An NDE measurement model functions to predict the measurement response of a sample for a NDE technique using first principles. The components of an NDE measurement technique model are shown in Figure 1.2 for the case of an ultrasonic technique. A complete system model encompasses three major components: a source, a sample, and a receiver. The source component of the model defines the incident field in the sample through representation of the input signal, source hardware, electrical connection, source transducer, and the transducer interface condition with the sample. Given the incident field, the scattered field can be calculated by the sample component model, given the material properties, sample geometry and flaw characteristics. Depending on the measurement technique, significant material properties can include elastic properties, electrical conductivity, thermal conductivity and density. Sample geometry including domain size (finite or infinite) guides the selection of the appropriate model. Flaw characteristics include type (cracks, voids, porosity, corrosion, disbonds, damage), geometry, and condition (such as the interface condition between crack faces). The reception component transforms the scattered field into measurement data through a relationship defined by the transducer interface condition, receiver transducer, electrical connections and data acquisition hardware. The model for each component is typically designed in order to provide the most accurate representation of a measurement technique while minimizing computational effort.

Figure 1.3 displays a summary of the role of modeling in NDE technique development. Models can produce significant benefits at several stages of the NDE technique development process. First, models can be used to aid in the interpretation of raw data. With this understanding, modeling can be beneficial in selecting the appropriate features for classification. Also, the inspection setup including for example, ultrasonic transducer design, eddy current coil design, x-ray radiography parameters can greatly benefit from accurate measurement models. For the development of automated inspection techniques, models can expand the training data set, thus reducing sample costs. Models can also be directly incorporated into feature classifiers through inverse methods. During the validation process, models can be used to verify the robustness of the classification technique while again reducing sample costs. In addition, models can be beneficial in displaying an understanding of the inspection problem to project sponsors and can be helpful during the instruction of the inspectors. Lastly, models can also be used to

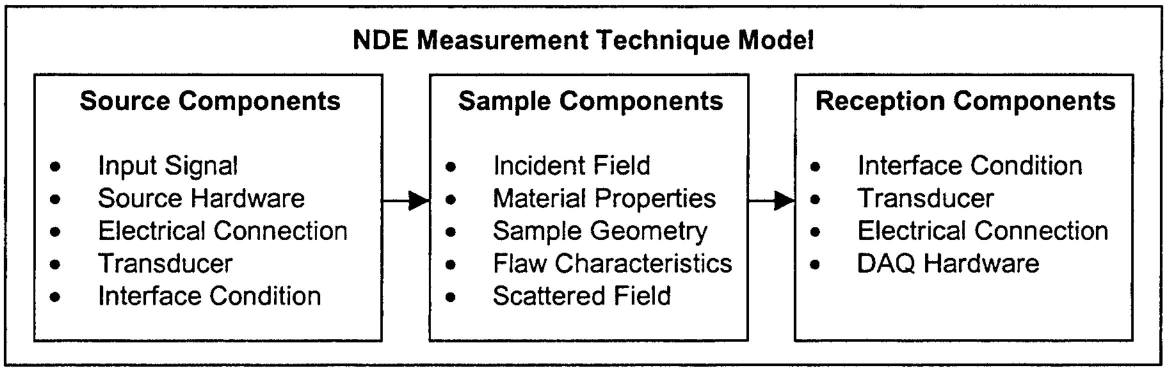

Figure 1.2. Components of NDE measurement technique model.

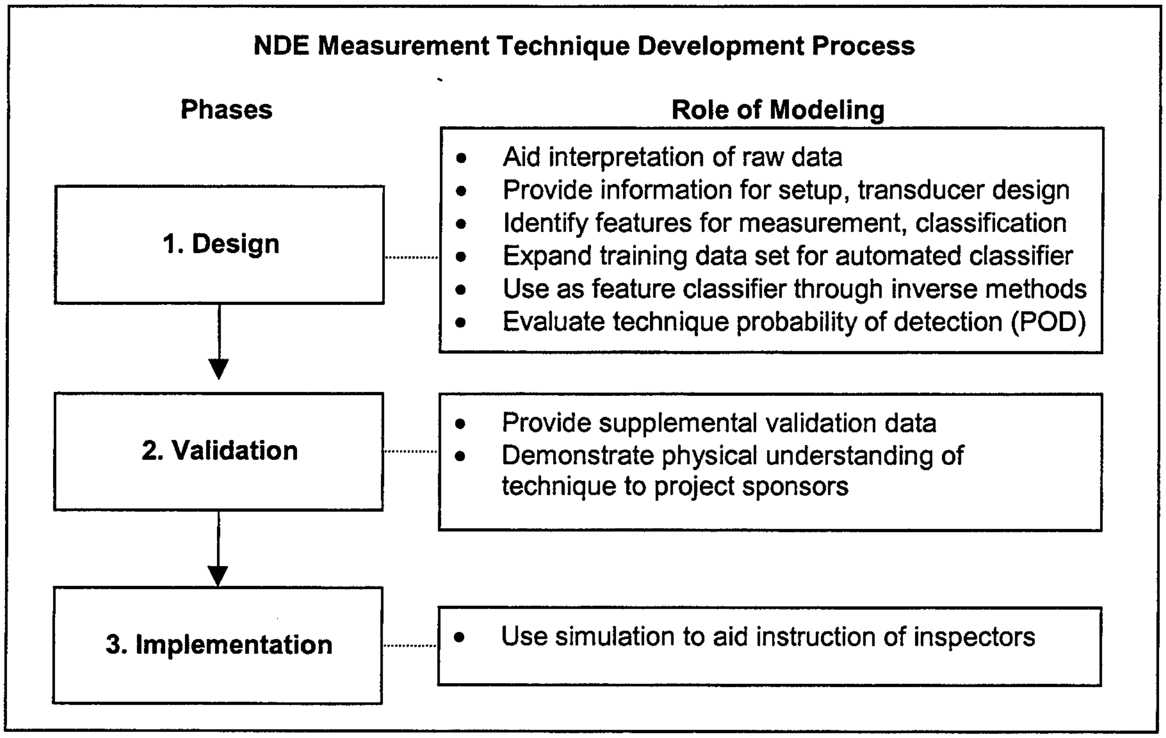

Figure 1.3. Role of modeling in NDE technique development process.

evaluate the reliability of an NDE technique through the calculation of the probability of detection (POD). A recent report by Matzkanin and Yolken (2001) assessed the current capability to simulate POD for NDE. Further discussions of the benefits of modeling can be found in papers by Coffey (1988) and Achenbach (1999).

The goal of this report is to present a broad overview of mathematical modeling in nondestructive evaluation. Although many significant texts and papers have been written that address both select model components and system approaches, only a few works have addressed the subject generally. Prior general works on mathematical modeling in NDE include Blackmore and Georgiou (1988), Gray et al. (1989) and Achenbach (1999). The primary emphasis for this work is to further expand the reviews of NDE modeling literature covered by these general works. To provide a starting point for researchers and engineers, the discussions and references will include multiple modeling approaches (analytical, asymptotic, and numerical) for a variety of NDE techniques. Analytical approaches evaluate the exact solution to fundamental problems based on first-principles. Asymptotic methods formulate expressions that approximate the solution to problems where exact solutions are unavailable. Numerical modeling approaches are applied to complex problems to transform the model space to a series of coupled fundamental problems that can be efficiently solved by a computer. Also, the presentation of NDE modeling software packages in the literature has typically been limited to a single package for a particular application. A second emphasis for this report will be to present the pertinent modeling software packages for a variety of NDE techniques.

1.2 Scope of Overview

In the next section, Section 2.0, an overview of modeling for four NDE techniques, ultrasonic testing, eddy current testing, radiography, and thermography, is presented. In order to present the broad subject of NDE modeling for this report, the discussions of modeling research and software packages are limited in scope at this time. Introduction references are provided in each section for the purpose of further study by the reader.

Given the inherent depth of the field and background of the author, an emphasis is given to ultrasonic nondestructive evaluation. Section 3.0 provides separate discussions on the generation of ultrasound, wave propagation in elastic solids, scattering from cracks, and waves in guides and at interfaces.

The report concludes with Conclusions and Prognosis in Section 4.0. Due to the quantity of references and to facilitate their use, the references are presented after each discussion in the sections.

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2.0 OVERVIEW OF MODELING IN NDE

2.1 Ultrasonic Techniques

2.1.1 Discussion

Introductions to modeling in ultrasonic nondestructive evaluation can be found in the following works: Thompson et al. (1984,1985), Gray et al. (1986,1988,1989), Georgiou and Blackmore (1989), Heyman (1989), Achenbach (1992), Thompson and Thompson (1992), Krening and Shmits (1996), Schmerr (1998), Spies (1999a,1999b). The basis for ultrasonic NDE modeling is the elastodynamic equations of motion derived from the theory of elasticity. Research into ultrasonic NDE measurement models has concentrated on two fundamental components, the ultrasound source, and the propagation of waves in a specimen for a variety of material properties, sample geometries and flaw characteristics.

Models for the generation of ultrasound are important for the design of nondestructive testing systems and interpretation of test data. Analytical and asymptotic approaches have been used to obtain expressions for the field of an ultrasound source. Numerical methods have also been applied to simulate the field for complex source designs. An overview of work on the generation of ultrasound is presented in Section 3.1.

Analytical and asymptotic methods have been developed to model the propagation of waves in elastic media for fundamental cases. A discussion of prior work and current problems in wave propagation in elastic media is presented in Section 3.2. One significant goal of ultrasonic NDE modeling is the development models for the detection and characterization of fatigue cracks. Approximate methods such as Kirchhoff theory and geometric theory of diffraction have been used to model the scattering from cracks. Numerical methods and interface conditions have been developed to better simulated the scattering from real cracks. An overview of research into the scattering of elastic waves by cracks is presented in Section 3.3. Guided waves have been explored for materials characterization of thin and layered structures.

Analytical solutions for the fundamental the problems of waves on an elastic half-space (Rayleigh waves) and in a plate (Lamb waves) have been extensively applied to ultrasonic NDE technique development. Research into analytical and numerical methods has continued to address guided waves in composite structures with complex material properties (anisotropic, inhomogeneous) and geometric characteristics (layered media, varying curvature). A discussion of modeling research for waves in guides and at interfaces will be presented in Section 3.4.

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2.2 Eddy Current Techniques

2.2.1 Discussion

Introductions to modeling of eddy current inspection can be found in works by Auld et al. (1981) and Gray et al. (1989). An eddy current inspection is conducted through the measurement of the impedance change at the probe terminals to detect surface and sub-surface flaws in a material sample. By application of the electromagnetic reciprocity relation, this measurement can be calculated through integration of the electromagnetic field over the sample surface surrounding a flaw. Maxwell's equation can be solved in order to calculate the electromagnetic field for the combined system of probe, sample and flaw. Exact and asymptotic methods have been applied to fundamental problems. To address the solution for a variety of complex probe designs and test sample configurations, computational methods have been developed and successfully applied.

Numerical modeling approaches that have been used for eddy current modeling include the finite difference method, the finite element method (Palanisamy and Lord, 1979,1980; Ida et al., 1983; Palanisamy and Thompson, 1984; Allen et al., 1985; Ida and Lord, 1985; Lord et al., 1988; Ludwig et al., 1990; Shi and Ludwig, 1996; Kobidze and Lord, 1998), the boundary element method (Beissner, 1986, 1991; Chao et al., 1995; Ludwig et al., 1998), and the volume integral approach (Bowler et al., 1989). Various software packages have been developed for possible application to eddy current NDE modeling: MMP by Hafner of ETH Zurich using a semi-analytic method (Hafner and Ballisti, 1989), MESSINE in CIVA by CEA using a semi-analytic method (Lhémery, 1999), ECSIM by CNDE at Iowa State University using BEM (Schmerr, 1999), TRIFOU by EDF using an FEM-BEM approach, OPERA-3D by Vector Fields using FEM (Emson and Simkin, 1990), PODET by AEA Technology using OPERA (FEM) and POD calculations (Wall, 1997), and VIC-3D by Victor Technologies using the Volume Integral Approach.

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2.3 Radiography

2.3.1 Discussion

An introduction to the modeling of radiographic testing can be found in the works by Gray et al. (1989), and Tillack (1999). A model for a radiographic inspection technique consists of three components: the radiation source, the interaction model of the beam with the sample, and the radiation detector. A source model for an x-ray beam, determined through application of first principles, consists of geometric characteristics (focal spot, density distribution), the energy spectrum and filtering. The interaction of the beam with the sample can be defined in terms of material attenuation, according to an attenuation law (Gray et al., 1989), and beam scattering. Two approaches are often used to describe the scattering of the beam within the material: a straightforward analytical description, and Monte Carlo simulations, which are more accurate but computationally intensive. Detector models have been developed for radiographic film and real-time radiography equipment (Tillack, 1999).

Three-dimensional radiographic imaging models that generate two-dimensional film images have been developed (Gray, 1988; Wang and Rokhlin, 1988) and integrated into NDE simulation packages (Tillack,1999). Software packages that have been developed for x-ray NDE simulation include: XPOSE and NNXPOSE by AEA Technology (Wall, 1997), a computer package by BAM (Tillack,1999), Sindbad by CEA-LETI (Lhémery, 1999), and XRSIM by CNDE at Iowa State University (Inanc and Gray, 1997; Schmerr, 1999, Gray, 2000).

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2.4 Thermography

2.4.1 Discussion

An introduction to modeling of thermal NDE techniques can be found in the work by Marinetti et al. (2000). The heat equation is the basis for the modeling of thermal NDE techniques. Numerical techniques such as the finite difference method (FDM) and the finite element method (FEM) are well suited for such problems, but can be computationally intensive. To simplify the analysis in order to provide both depth information and insight into the thermographic process, a first-order calorimetric model was derived by Perez et al. (1998a). Other recent thermography modeling works include Killey and Sargent (1989), Nicolaides and Mandelis (1997), Perez et al. (1998b), Karpen et al. (1999), Marinetti et al. (1999), Plotnikov (1999) and Vavilov (1999).

Commercial FEM, FDM and boundary element method codes for heat transfer modeling have been used for thermal NDE modeling. Viable software packages include: SINDA/G and SINDA/3D by Network Analysis Inc. using FDM, SAMCEF and MECANO THERNL by Samtech using FEM, and KELVIN and CELSIUS by Integrated Engineering Software using the boundary element method.

2.4.2 References

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3.0 REVIEW OF ULTRASONIC NDE MODELING

3.1 Ultrasonic Transducer Modeling

3.1.1 Discussion

To model ultrasonic nondestructive evaluation techniques, the source of the ultrasound, often a piezoelectric transducer, must be accurately represented. Introductions to transducer modeling can be found in Harris (1981), Weight (1987), Krautkramer and Krautkramer (1990), Lhémery(1994a) and Schmerr(1998).

Early work addressed the near and far field response to a baffled piston in acoustic media. A harmonic point source solution was developed by Miller and Pursey (1954). Freedman (1960) solved the near field solution for the rectangular piston in an acoustic field using phase approximations. Zemanek solved the near and farfield of a vibrating circular piston through numerical integration of the double integral. Fourier transform approaches were used by Lockwood and Willette (1973) to solve harmonic excitations of a piston. An impulse response approach was developed by Stepanishen (1970) to evaluate the near and far field transient radiation by a piston in a rigid baffle.

Numerical approaches have been used to solve for the transducer field in elastic domains. Kawashima (1984) evaluated the integral representations numerically for each point in the transducer field. The finite element method has been shown to produce accurate transducer field results (Ludwig and Lord, 1988; Xue et al, 1995) but with some computational expense. The software package, PZFlex, developed by Weidlinger Associates, was designed to simulate piezoelectric transducers using FEM.

Weight (1987) used the geometric theory of diffraction to approximate the field generated by transducers. Schmerr and Sedov (1988) used high frequency asymptotic solutions to obtain simple analytical expressions for the radiated elastodynamic field. Following the impulse response approach of Stepanishen (1971), Lhémery (1994a, 1994b) developed an analytic expression for the approximate solution based on a new integral formula for arbitrary transient ultrasonic fields radiated into a solid.

Paraxial approaches have been shown to be valuable in approximating the transducer field while reducing the computational solution time required by other approaches (Schmerr, 2000). Gaussian-Hermite functions have been used to implement this modeling approach and these models have found good agreement with numerical simulations for many measurement conditions (Minachi et al.,1993). A multigaussian ultrasonic beam model has been shown to apply to a wide range of inspection materials and geometries while remaining computationally efficient (Wen and Breazeale, 1988; Schmerr, 2000).

Models examining the dynamic response of piezoelectric disks were explored by Guo and Cawley (1991), Guo et al. (1992), Ogilvy (1996). Piezoelectric polymer films (such as PVDF) were studied by Wilcox et al. (1998). Due to the potential benefit, modeling of ultrasonic transducer arrays has been extensively examined (Ullate and San Emeterio, 1992; McGarrity et al., 1994; Powell and Gordon, 1996a, 1996b; Rose et al., 1998; Reynolds and Hayward, 1998; Deutsch et al., 1999,2000; Zhang et al., 2000, Lupien and Cancre, 2001).

Unlike contact transducers or immersion testing, air-coupled transducers, electromagnetic-acoustic transducers (EMATs) and laser ultrasonics require no contact or fluid coupling with the sample. Models addressing air-coupled transducers were explored by Safaeinili et al. (1995), Castaings et al. (1998), and Lobkis and Chimenti (2000). Models of electromagnetic-acoustic transducers (EMATs) have been studied by Vasile and Thompson (1979), Ludwig et al. (1993), Thompson (1993), and Spies et al. (1996). Due the potential benefit as a non-contact inspection technique, models for the generation of ultrasound by laser sources have been extensively studied (Sullivan et al., 1988; Candy et al., 1996; Grand et al., 1996; Doyle and Scala, 1996; Yang et al., 1997; Lafond et al., 1998; Murray et al., 1999).

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3.2 Wave Propagation in Elastic Solids

3.2.1 Discussion

The theoretical basis for wave propagation in elastic solids can be found in texts by Achenbach (1973), Auld (1973), and Graff (1991).

A straightforward means of representing elastic wave propagation is through ray theory. Thus, the direction of propagation of disturbances corresponds to the direction along rays. The theory for modeling waves in elastic solids as rays can be found in the text by Achenbach et al. (1982). Many software packages have been implemented based upon ray theory, the geometric of diffraction and paraxial beam models (Schmerr, 1998, 2000). Such packages include: MUSE and AUTOMUSE by AEA Technology; CIVA (Champ-Son, Méphisto) by CEA (Lhémery, 1999); UTSIM by CNDE of Iowa State University (Schmerr, 1999); RayTrace by Spanner of EPRI; UltraSIM by FORCE Institute; CADMUS by Fraunhofer-Institute for Nondestructive Testing (Spies, 1996); Ultrasonic Ray Tracing Software for AutoCAD by Reilly of NDTSoft; and Imagine3D by UTEX Scientific Instruments Inc.

Welds are presented as a challenging example for ultrasonic inspection modeling. Welds are typically inhomogeneous, anisotropic and complex geometrically. Weld flaws can include fatigue cracks, slag inclusions and porosity. The following are papers that explore models for the ultrasonic inspection of welds (Bostrom, 1980; Rokhlin and Bendec, 1983; Rokhlin et al., 1984; Rokhlin and Adler, 1984; Ogilvy, 1985, 1986,1988; Fiedler et al., 1986; Gray et al., 1988; Nagy and Adler, 1988; You et al., 1988; Ogilvy and Temple, 1990; Bond and Taylor, 1991; Rudlin and Wolstenholme, 1992; Minachi et al, 1993; Bihn and Weiland, 1998; Lhémery et al, 2000; Spies, 2000). Additional examples of complex material and geometry modeling will be presented in the Sections 3.3 and 3.4.

3.2.2 References

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3.3 Scattering of Ultrasonic Waves from Cracks

3.3.1 Discussion

An introduction to models for the ultrasonic inspection of cracks can be found in the following works (Gray and Thompson, 1986; Gray et al., 1988; Achenbach, 1992; and Schmerr, 1998.) The Kirchhoff approximation and asymptotic approaches such as geometric theory of diffraction have been found to be useful models for many crack inspection problems (Achenbach and Norris, 1981; Coffey and Chapman, 1983, 1984; Thompson and Gray, 1984; Schmerr and Sedov, 1984; Temple, 1986; Spies, 1996; Butin et al, 1998).

Numerical methods have been found to properly simulate the scattering solution from cracks. Such approaches include the finite difference method (Georgiou and Bond, 1987; Datta et al., 1992), the finite element method (Lord et al., 1988; Lin et al., 1991; Safaeinili and Roberts, 1994; Zgonc and Achenbach, 1996; Lowe et al, 1998; Kishore et al, 2000; Yang et al., 2000), the boundary element method (Niwa et al, 1986; Beskos, 1987; Burdreck and Achenbach, 1988; Jia et al., 1990; Beskos, 1997, Aldrin, 2001), the finite integration technique (FIT) (Schuhmacher et al., 1994; Schmitz et al., 1995), and Fourier transform of integral representations (Bovik and Bostrom, 1997). Hybrid approaches combining multiple solution methods have also been developed (Blake and Bond, 1990; Liu and Datta, 1993; Chang and Mal, 1999).

Real crack face surfaces exhibit conditions that are not represented by ideal crack models. Crack surfaces can be in contact and have significant roughness. Papers examining inspection models with real crack interface conditions include Thompson and Fiedler (1984), Punjani and Bond (1986), Thompson et al. (1986), Rehbein et al. (1986, 1988, 1990), Buck et al. (1988), Hirose and Kitahara (1991), Ogilvy and Culverwell (1991), Bostrom (1993), Bostrom et al, (1994), Eriksson et al, (1995), Solodov (1998).

A subset of crack inspection modeling includes stress corrosion cracking. Due to the existence of widespread corrosion in aging aircraft and infrastructure, the detection of stress corrosion cracks is of concern. Recent paper that address models for the inspection of stress corrosion cracks include Newberry et al. (1988) and Pan et al., (1999).

In addition to the ray method and geometric theory of diffraction modeling packages presented in the previous section, software packages incorporating numerical methods have been developed to simulate the inspection of cracks. Such packages include: Wave2000 by CyberLogic using the finite difference method (Kaufman et al., 1999), and SUNDT (UTDefect) by Dept. of Mechanics - University of Chalmers (Bovik and Bostrom, 1997).

3.3.2 References

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3.4 Ultrasonic Wave Propagation in Waveguides and at Interfaces

3.4.1 Discussion

The propagation of waves in elastic solids with geometries of finite dimension relative to the wavelength and the propagation of waves at material interfaces are addressed in this section. Guided wave techniques provide the capability to measure local material properties and detect defects such as disbonds, damage, fatigue cracks and corrosion. Introductions to these models can be found in works by Viktorov (1967), Thompson et al. (1989), Lowe (1995), Chimenti (1997), Wu and Liu (1998), and Spies (1999).

The formulation for waves that propagate along the surface of an elastic half-space was first investigated by Rayleigh (1889). Lamb derived expressions for the propagation of waves in a plate in terms of symmetric and antisymmetric modes (1917). The solution for guided waves in plates was found to exhibit velocity dispersion as a function of frequency. Love demonstrated the existence of transverse modes for plates and layers (1911). Through application of the appropriate interface conditions, wave propagation in an arbitrary number of layers can be formulated. Reviews of modeling for guided waves in plates and layered media can be found papers by Lowe (1995) and Chimenti (1997). Recent works addressing the development and application of models for guided waves include Viktorov (1967), Nayfeh et al. (1979, 1981), Bostrom (1983), Niwa and Hirose (1985), Arnold and Felsen (1986), Lin et al. (1990), Yuan and Nazarian, (1993), Chimenti and Lobkis (1998), Cho (2000), Cetinkaya and Li (2000), Cho and Lin (2001). A software package, DISPERSE, has been developed by the NDT Lab of Imperial College to solve for the dispersion curves for layered media for a variety of material and geometric conditions.

The modeling of ultrasonic NDE of composite materials, composed of multiple layers and/or embedded fibers has been an active area of research due to the need to characterize the material properties and assess their condition in the field. Papers addressing the development and application of guided wave modeling for composites include Nasser and Nayfeh (1982), Nayfeh et al. (1984), Shaikh et al. (1987), Chimenti and Nayfeh (1988), Datta et al. (1988), Margetan et al. (1988), Nayfeh and Chimenti (1988), Nayfeh et al. (1988), Qu and Achenbach (1988), Thompson and Newberry (1988), Clark and Iyer (1989), Mal and Taylor (1990), Olsson et al. (1990), Thompson et al. (1991), Datta et al. (1992a, 1992b), Ju and Datta (1992), Kohl et al. (1992), Dayal (1995), Chu et al. (1995), Yim and Williams (1995), Ogilvy (1995), Safaeinili et al. (1995), Rokhlin et al. (1995), Chimenti and Auld (1995), Spies and Kroening (1996), Huang et al. (1997), Castings et al. (1998), Rokhlin and Huang (1998), Rehman et al. (1998), and Nesvijski (1999).

Models of wave scattering at interfaces are used to study the effect of real features such as roughness, imperfect bonds, stiffness layers, and porosity. Papers addressing the development and application of models for waves at interfaces include Stoneley (1924), Achenbach and Epstein (1967), Rokhlin and Rosen (1981), Baik and Thompson (1984), Ng and Ngoc (1988), Sotiropoulos and Achenbach (1988), Buck et al. (1989), Mal et al.

(1989), Ogilvy et al. (1989a, 1989b), Rose et al. (1992), Margetan et al. (1992), Chu et al. (1992), Chivers (1992), Ogilvy (1992), Nagy (1992), Yalda-Mooshabad et al. (1992), Rokhlin et al. (1993), Cawley and Pialucha (1993), Pecorari et al. (1995), Challis et al. (1996), Lian et al. (1996), Delsanto et al. (1998), Lavrentyev and Rokhlin (1998), and Rose et al. (1998).

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4.0 CONCLUSIONS AND PROGNOSIS

4.1 Discussion

Models for ultrasonic testing, eddy current testing, radiography, and thermography have reached a level of sophistication such that the development of a wide variety of NDE techniques can be addressed computationally. As an example, the design and selection of ultrasonic transducers and eddy current probes have significantly benefited from a variety of accurate modeling techniques. However, it must be noted that the wide acceptance and everyday use of modeling as a practical tool in NDE has not occurred throughout the industry. The following issues have been sited:

- Models require excessive development cost and time
- Accurate simulations are often computationally intensive
- Models often lack consistent accuracy with experimental results from the field

To properly address these issues, a strategy is proposed that encompasses the key parties in the NDE community: the NDE leadership and funding organizations, the NDE research community, and the NDE applications community. In order to address these issues, the following tasks have been identified for each group.

A. Tasks for NDE leadership and funding organizations:

- Support development of databases of current and potential applications of NDE modeling techniques to direct research and development.
- Complete a preliminary cost benefit assessment of current and potential NDE modeling capabilities and identify key areas for research and application funding.
- Promote and support the development of measurement models by the research community.
- Promote and support the transfer of measurement models from the research community to the applications community.
- Promote and support the implementation of NDE modeling software packages by the applications community for broad community use.
- Provide a repository for NDE modeling tools (Matzkanin and Yolken, 2001) that offers flexibility for broad NDE community support. A five part approach is proposed:
    1. Repository for shareware software (not refereed) available to the NDE community,
    2. Repository for refereed software available to the NDE community,
    3. Repository for software developed by and shared within a sponsoring consortium,
    4. Database of available commercial NDE modeling software,
    5. Database of available NDE modeling services.

B. NDE measurement model development tasks for NDE research organizations.

- Continue development of mathematical models for emerging NDE transducers technologies.
- Continue research into the scattering of waves (and the dispersion of heat) by discontinuities in structures in close proximity to complex geometric features such as fastener sites, joints, and welds.
- Continue research into the scattering of waves (and the dispersion of heat) by discontinuities in composites, smart materials, and MEMS.
- Continue research into modeling of guided waves in structures with varying curvature and residual stress.
- Improve efficiency of model calculations for complex 3D geometries.
- Continue development of hybrid modeling approaches. Develop adaptive hybrid modeling schemes that incorporate artificial intelligence to select the best modeling approaches for the appropriate sample regions.
- Validate simulations for both artificial and real flaws with experimental data such that NDE flaw characterization approaches are in agreement. Continue research into model corrections necessary for accurate simulation of real flaws.

C. NDE modeling software development tasks for NDE application organizations:

- Incorporate promising modeling approaches from NDE research community.
- Improve the ease to construct a model in an NDE modeling software package for an in-field application. Provide capability to import CAD drawings into NDE modeling software packages when appropriate.
- Provide indications to the operator when regions of a simulation that is based on an approximate method are no longer valid.
- Develop model software packages that incorporate hybrid models, which apply the most efficient modeling approaches to the appropriate sample regions.
- Provide means to perform parametric design studies in NDE modeling software packages.
- Integrate NDE modeling software packages with automated signal classification (ASC) development environments to streamline ASC algorithm development process.
- Provide means to simulate the effect of variation in model application parameters on NDE technique POD capability.

Through application of this strategy to NDE measurement model development, consistent improvement in the reliability of the testing techniques would be achieved while providing significant cost avoidance and time savings. To implement this approach, better cooperation between research, application, and funding organizations is necessary. As proposed by Matzkanin and Yolken (2001), a consortium with significant support from the major NDE funding organizations, the primary NDE research organizations, and industry would provide a significant focal point to guide this endeavor.

4.2 References

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14. ABSTRACT This report presents a broad overview of mathematical modeling in nondestructive evaluation (NDE). The primary emphasis is to expand the reviews of NDE modeling literature covered by previous general works. To provide a starting point for researchers and engineers, the discussions and references include multiple modeling approaches (analytical, asymptotic, and numerical) for a variety of NDE techniques. A second emphasis for this report is to present the pertinent modeling software packages for a variety of NDE techniques. Overviews of modeling for four NDE techniques, ultrasonic testing, eddy current testing, radiography, and thermography are presented. In order to present the broad subject of NDE modeling for this report, the discussions of modeling research and software packages are limited in scope; however, numerous references are provided in each section for further study by the reader. Given the inherent depth and importance of the field, special emphasis is given to ultrasonic NDE. Discussions are presented on the generation of ultrasound, wave propagation in elastic solids, scattering from cracks, and waves in guides and at interfaces.

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