Elastic wave propagation in anisotropic, inhomogeneous materials

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application to ultrasonic NDT

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Title of research project:

Simulation and implementation of ultrasound based inspection methods for materials and material combinations difficult to inspect.

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Chapter 1

Introduction

In this chapter the field of ultrasonic Non-Destructive Testing (NDT) is shortly reviewed from its infancy, through the intense development it has undergone and up to today where it's present state as an advanced technology has positioned it as an effective and reliable tool for performing non-destructive testing.

The presentation then focuses on the activities of FORCE Institute within this area. With numerous competitors offering their services on this market and with authorities (especially within the nuclear sector) pushing standards on safety, reliability and effectiveness, it is vital that the company possesses the newest technology and knowledge within the field.

Finally, the aim of the current project is presented and justified in the light of this demanding environment.

1.1 History of ultrasonic NDT

The study of ultrasonics, i.e. high-frequency sound above the human hearing threshold started in the 19'th century, when it became possible to generate high frequency elastic waves in materials. Major breakthroughs were the discovery of magnetostriction in 1847 by Joule and the piezoelectric effect in 1880 by the Curie brothers. The discovery of these electrical-to-mechanical mechanisms played a crucial role for the development of ultrasonic NDT. The first practical applications of ultrasonic NDT were based on through-transmission (detection on opposite surfaces using a transmitter and a receiver) of continuous waves around 1930. The pulse echo method (detection from one side only using a transmitter and a receiver which may be identical) was introduced around 1940 by Firestone, USA and is the preferred method of ultrasonic testing today for several reasons, one of them being the often occurring situation with access restricted to one material surface only. World War II also played a major role in the development of ultrasonic NDT.

At this point, it is worth mentioning the most important reasons for the success of today's ultrasonic inspection. These are the following [10]

- testing may be carried out from a single surface
- high degree of penetration in many commonly-used materials
- accuracy in locating and measuring defects

- ability to detect and size very small defects
- compatibility with automatic scanning devices and computers

There are also some drawbacks to the method, the most serious being

- the operator must be properly trained and highly experienced for a reliable result
- large surfaces may require a large time of operation
- most transducers in use today require a high degree of coupling between the transducer and the surface to be scanned

An ultrasonic inspection typically involves a transmitter for exciting a sound field in the material as well a receiver for picking up echo signals from a defect in the material as shown in Fig. 1.1. Recorded ultrasonic data is typically visualized in one of the following

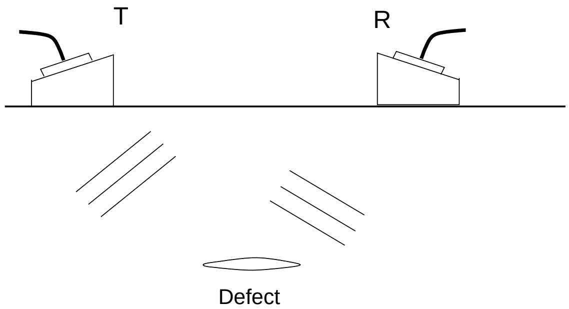

Figure 1.1: The basic principle of ultrasonic testing of a defect in a material using a transmitter (T) for exciting elastic waves and a receiver (R) for detecting echoes from the defect.

basic ways

- **A-scan**: The receiver is fixed at a certain position, and the amplitude of the recorded signal is shown as a function of time.
- **B-scan**: The receiver moves along a straight line picking up an A-scan at each position. The maximum amplitude from each A-scan is shown in the form of a color plot indicating the amplitude as a function of material depth or time along one axis (distance and time are equivalent for a known material) and surface position along the other axis.
- **C-scan**: The receiver scans a plane surface and at each position the maximum amplitude in the corresponding A-scan is recorded. The resulting picture is a color plot indicating the maximum amplitude at each position on the surface. In this representation, the depth information is lost.

From these scan types, so-called through-transmission scans and P-scans (Projection scans concept developed by FORCE Institute) may be constructed. In the latter, C-scans are presented for the upper surface, the side surface and the end surface of a material. Illustrations of these scan types are given below.

The availability of fast and cheap electronics including computers has automated and made more effective many of the tasks associated with an ultrasonic inspection. The process of scanning the surface, i.e. transmitting and receiving, is today in many cases performed by automatic scanners which may be controlled entirely by external control systems or using a robot, the latter method being particularly relevant for surfaces of complex geometries. An example is shown in Fig. 1.2, where an automatic weld scanner (from FORCE Institute) is inspecting a pipe. For analysis and visualization of the re-

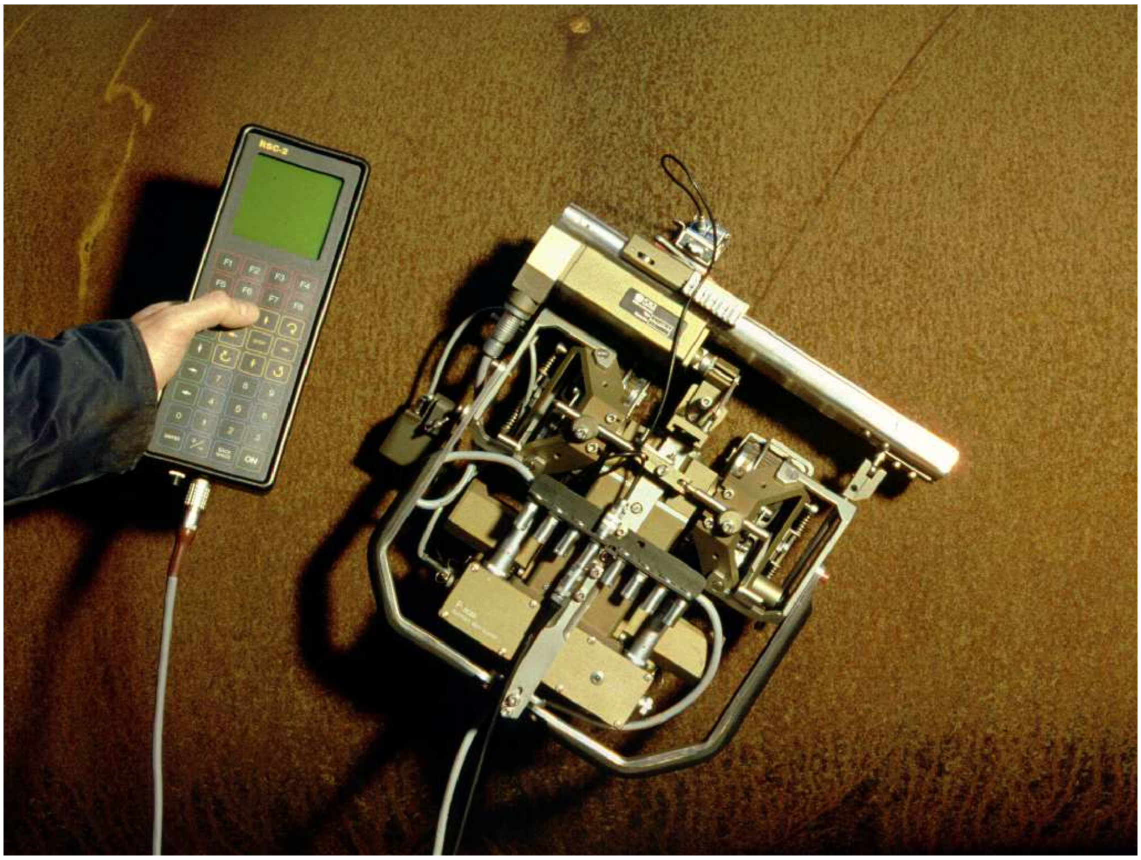

Figure 1.2: Example of an automatic weld scanner (AWS-5D) from FORCE Institute for inspection of a pipe. The scanner moves along the weld seam, while the transmitter/receiver placed on top of the scanner may be positioned on any desired position along the rail. The motion of the scanner may be controlled entirely by an external scanner control or through a remote control (shown in the picture). The external control also handles the transfer of ultrasonic data for analysis (see Fig. 1.3). Due to the curved pipe surface, magnetic wheels on the scanner are required.

ceived ultrasonic data, advanced software packages are often used. An example of such a software package is shown in Fig. 1.3 illustrating the user interface of the PS4 program developed by FORCE Institute. This software may also be used to program and control the movement of the scanner as discussed above. The figure contains an A-scan (right), through-transmission scan (lower left) and finally, top-, side- and end view (upper right).

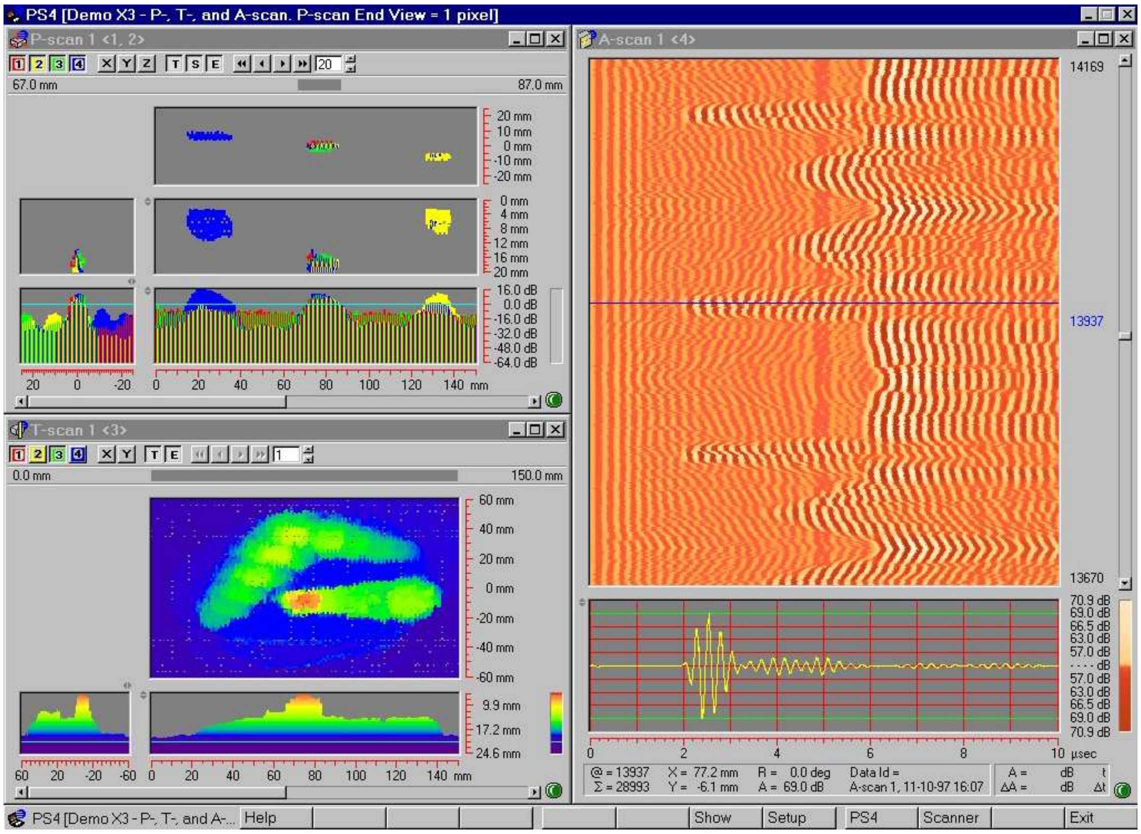

Figure 1.3: Example of the user interface for the PS4 software package for analysis and visualization of recorded ultrasonic data. Several types of representations (scan types) of the recorded echo signals from a defect in a material are shown.

1.2 Ultrasonic NDT at FORCE Institute in a changing environment

FORCE Institute offers advanced ultrasonic inspection services to a number of different industrial sectors, national as well as international, involving many different types of materials. Typical sectors are (with the typical inspection job mentioned in parenthesis)

- Nuclear and conventional power plants (inspection of all types of steel welds with a large range in dimensions)
- Petro-chemical plants (corrosion inspection of base materials and weld inspection)
- Refineries (do.)
- On- and offshore industry (do.)

These activities require an ongoing research and development of scanners and software for manipulating these as well as for analysis and visualization of recorded ultrasonic data. Two results of this development have already been presented in Fig. 1.2 and Fig. 1.3.

However, one important point has not been addressed so far. Today, the data analysis performed in many software packages (as for example PS4 described above) is based on the assumption that the material inspected is isotropic and homogeneous. That is, the elastic waves propagate with the same velocity in all directions and the material properties are the same throughout the material. Based on these assumptions and the recorded ultrasonic data, software packages are able to calculate the position, orientation and size of a defect in a material as illustrated in the simple Fig. 1.1. Furthermore, for these types of materials, inspection procedures have been optimized with regard to transmitter angle, frequency, position etc. These assumptions are true in many ultrasonic inspection situations.

Over the last decades, ultrasonic NDT has found new areas of application and new types of materials have emerged. As a result, the above simplified material assumptions may no longer be true in all cases. The new types of materials encountered in practice may be of anisotropic nature (direction dependent sound velocity) or possess a pronounced degree of inhomogeneity (material parameters vary throughout the material) or even both. Examples of anisotropic materials are fiber reinforced materials and crystalline materials with a dominating grain orientation such as austenitic welds. Examples of inhomogeneous materials or components are fiber composites, concrete as well as bimetallic - and austenitic welds. These materials are either already relevant or are expected to be of relevance in the future for ultrasonic NDT. Thus, although the above basic principles for analysis may be applied to these materials in practice with some success, there is a growing need for a correct understanding of elastic wave propagation in these advanced materials. This knowledge may be provided through an activity such as mathematical modelling, a point of view which is elaborated on in the following section concerning inspection qualification.

1.3 The qualification process

A critical point in the process of obtaining an inspection job is the qualification procedure normally specified by the customer. In the qualification procedure, the company offering it's inspection services must document that it is actually capable of carrying out the inspection procedure in a satisfactory way and that the result of the inspection is trustworthy.

In principle, the qualification procedure may vary from customer to customer. However, an attempt to provide a general framework for the development of qualifications (a recommended practice) for inspection of specific components has been made by ENIQ (European Network for Inspection Qualification) under the European Commission. This attempt should ensure that the development of qualification procedures takes place in a coherent and consistent way throughout Europe [24, 25].

According to ENIQ, the qualification procedure should be the sum of the following two items

- non-blind or blind practical assessment, that is whether the defects are known in advance or not, conducted on simplified or representative test pieces resembling the component to be inspected.
- technical justification (TJ), which involves assembling all evidence on the effectiveness of the test, including previous experience of its application, experimental studies, *mathematical modelling*, physical reasoning (qualitative assessment) etc.

The aim is that the practical assessment together with the technical justification should provide convincing evidence to the costumer that the proposed inspection will achieve the desired performance targets, in terms of defect detection and sizing capability. According to ENIQ, the technical justification forms a key part in the qualification. This is because practical assessments may be extremely expensive and time consuming to carry out, while at the same time they may not be very flexible. The first point may be due to the manufacturing of test pieces, for example manually manufactured welds with specified defects. It may be time consuming to set up and carry out the inspections on these test pieces. Furthermore, the inspection has in principle only been tested on these specified components. If new or changed demands should be introduced at a later point in time, new assessments must in principle be carried out.

Technical justifications, on the other hand, may prove much more cost-effective and flexible. Table 1.1 shows the different types of evidence to be included for different types of technical justifications (leftmost column) in an inspection qualification as suggested by ENIQ. As seen from the table, theoretical modelling is deemed very relevant when justifying an inspection procedure, extending a qualification to a different geometry, qualifying an upgraded procedure and qualifying for changed defect descriptions. Furthermore, theoretical modelling is deemed relevant when justifying use of test pieces and defect populations and extending the qualification to a different material structure. The other (three) types of evidence in the table are (briefly) 1) experimental evidence, which includes practical trials associated with previous qualifications, published inspections programs such as Progamme of Inspection of Steel Components (PISC) or the Defect Detection Trials (DDT), experimental studies and field experience results 2) parametric studies, which may be considered a special type of experimental evidence, where the effect of certain parameters such as surface roughness is investigated on simple test pieces 3) equipment and data analysis which is basically an evaluation of the appropriateness of the used equipment and data analysis used for the inspection.

Partly due to these ENIQ suggestions, it is expected that technical justifications using mathematical modelling will play an increasingly important role in the qualification procedure in the future.

Type of TJ	**Theoretical modelling**	**Experimental evidence** (1)	**Parametric studies** (1)	**Equipment and data analysis**
Justify inspection procedure	VL (2)	VL	L	L (3)
Justify use of test pieces and defect populations	L (4)	VL	L	U
Justify inspection equipment (5)	U	U	L	VL
Extend qualification to different geometry	VL	VL	L	U
Extend qualification to different material structure	L	VL	L	U
Qualify upgraded equipment or software	U	U	U	VL
Qualify upgraded procedure	VL	L	U	L
Qualify for changed defect descriptions	VL (2)	L	VL	U

Table 1.1: Different types of evidence for different technical justification (TJ) and their usefulness. Taken from [24]. VL: Very likely to contain evidence of this type. L: Likely to contain evidence of this type. U: Unlikely to contain evidence of this type. (1) For ultrasonic inspections of austenitic welds or cladding, any evidence provided under these headings is likely to include evidence relating to the material structure. (2) For ultrasonic inspection of welds or cladding, this may be reduced to L since modelling is less well developed for such materials. (3) Increase to VL if particularly demanding requirements are placed on the equipment or software, and this is not covered in a separate TJ. (4) May increase to VL for justification of worst case defects. (5) In some countries it is foreseen that for particular situations only qualification of the equipment is required. For these particular cases the technical justifications will mainly focus on equipment related issues.

1.4 Motivation and description of the project

It is important that a company with core activities within the area of ultrasonic NDT possesses sufficient knowledge about the often very complex propagation of elastic waves in anisotropic and inhomogeneous materials, and is able to transform this knowledge into a useful tool for carrying out inspection services correctly (including analysis and visualization) and for optimizing inspection procedures. Within the industry, it may postulated that while the technology involving scanners and post-processing software has undergone an intense development over the last decade or two, the fundamental understanding of the elastic wave propagation in these advanced materials has received far less attention. Today, many companies within this area have come to realize this fact, and as a result, research in terms of mathematical modelling of elastic wave propagation either within the company itself or through some sort of cooperation with a university is taking place.

These important issues concerning the development of appropriate knowledge and technology may be viewed as a reaction or response by a company to the changing environment and the competitors within this area. Another important concept is the Technical Justification described in the last section. As mentioned, it is not unrealistic to expect, that in light of ENIQ recommending mathematical modelling as part of a Technical Justification, this modelling activity will play an increasingly important role in future for ultrasonic NDT.

These observations have motivated the current industrial Ph.D. project. The project is concerned with mathematical modelling in anisotropic, inhomogeneous materials and the validation of this with experiments. The aim is through this modelling activity to obtain a better understanding of elastic wave propagation in these advanced materials. Through the acquired knowledge, it should be possible to set up optimal inspection procedures for a specific area in the material and transmitter/receiver characteristics. Based on gathered data from the model, identification and localization of interior defects should be possible.

The possible benefits of the outcome of the project have been analyzed from a strategic point of view in an internal business report [26].

1.5 Organization of thesis

The thesis consists of eight chapters. The content of these are as follows:

- **Chapter 1**: Provides a short review of the history of ultrasonic NDT including pros and cons of the technique together with a short description of the activities of FORCE Institute within this area. The need for a better understanding of elastic wave propagation due to the use of new and complex material structures is described. This need together with described initiatives from a number of European authorities have motivated the current project on mathematical modelling of elastic wave propagation.

- **Chapter 2**: The elastodynamic equations governing elastic wave propagation are presented. Emphasis is put on different relevant anisotropic materials through the description of their corresponding elastic matrices. A review is given of existing methods for solving the elastodynamic equations depending on the material situation considered. The choice of a numerical method in this project is described and motivated.

- **Chapter 3**: The theory of time-harmonic plane wave propagation is described and the use of this for providing valuable qualitative insight into elastic anisotropic behaviour is illustrated. An analytical solution to the problem of a line source on the free surface of an anisotropic medium is presented. Results from this analytic solution is compared with results from the numerical solution considered later in the thesis.

- **Chapter 4**: The numerical method considered in this project is described in detail. Models of piezoelectric transducers as transmitters and receivers are presented.

- **Chapter 5**: A number of simulations of wave propagation in anisotropic materials including scattering on specified defects are presented and interpreted. A-scan modelling is described in detail and a number of simulations and comparisons between different models are presented.

- **Chapter 6**: The austenitic MMA weld is considered as an example of an important anisotropic and inhomogeneous material component in ultrasonic NDT. A mathematical model of the crystal structure in the weld is described and a number of simulations are performed for different weld configurations.

- **Chapter 7**: A case study involving a typical component from a real ultrasonic NDT situation is presented. A material model of this component suitable for simulations is developed and presented. For a specified defect in the component, a parameter study demonstrates how the optimal transducer position (and frequency) may be found based on such simulations.

- **Chapter 8**: Provides a conclusion on the work presented in this thesis. Industrial aspects and benefits are then discussed. Finally, suggestions for further work are given.