A Narrowband Ultrasonic Spectroscopy Technique for the Inspection of Layered Structures

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ABSTRACT

This thesis introduces a narrowband ultrasonic spectroscopy (NBUS) technique for non-destructive testing. NBUS is most commonly used for inspection of multilayered structures. Inspections are performed by monitoring the electrical impedance of a transducer at a single frequency, the working frequency. A transducer's electrical impedance depends on the mechanical load on its surfaces. Acoustically coupling a transducer to an object changes its electrical impedance depending on the object's condition. This is utilized to detect defects in inspected objects.

Optimal transducer design and working frequency selection is addressed using modelling. Simulation results from a transfer matrix model of an evaluation setup is compared to results from FEA simulations. The transfer matrix model is used to calculate kinetic and elastic energy distributions in the inspected object as well as the effective electro-mechanical coupling coefficient (EMCC) of the setup. Transducer performance is explained using these quantities making it possible to optimize the transducer design.

NBUS has been successfully used for the inspection of carbon fibre reinforced panels (CFRP) and multilayered structures. Results from these inspections are presented.

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To Annelie

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Contents

Chapter 1

Introduction

1.1 Overview

This thesis presents a non-destructive testing (NDT) technique based on narrowband impedance measurements using ultrasound. Increased use of advanced materials such as multilayered aluminium structures and carbon fibre reinforced plastic panels (CFRP) in aerospace structures has lead to new demands on NDT tools. During the last century, a large amount of different techniques for NDT were developed based on different physical principles, e.g. x-ray, eddy current, thermography, shearography and ultrasonics.

The field of ultrasonics can be divided into subcategories, for instance ultrasonic resonance spectroscopy (URS). URS is, as the name implies, an ultrasonic approach to NDT utilizing resonances to evaluate the inspected material. The resonances of a mechanically excited object are valuable sources of information on the condition of the object. Several different techniques fall into the category URS differing in the procedure of spectrum acquisition and interpretation.

The technique in focus in this thesis is based on measurements performed using continuous wave excitation with a single working frequency. The resonance frequency of an ultrasonic transducer depends, not only on the design of the transducer, but also on the media on its front surface. The principle of the technique is that an ultrasonic transducer, acoustically coupled to an object under inspection, generates acoustic waves that propagate into the object and are reflected at boundaries and other discontinuities. The resulting wave pattern depends on the object and its condition. This in turn affects the electrical impedance of the transducer. Defects can be detected by monitoring the transducer's relative impedance change in the complex impedance plane. This technique is named narrowband ultrasonic spectroscopy (NBUS) throughout this thesis.

The work was funded by two EU projects, INCA and NANOSCAN. The participation in these projects involved the development and evaluation of URS methods to inspect carbon fiber reinforced plastic (CFRP) panels, cf. Section 6.2, and multilayered structures used in aerospace applications. Within the INCA project, special attention was given to a type of defects known as *kissing bonds*, cf. Section 6.3. After different URS approaches had been evaluated, work was devoted to the NBUS approach. This approach provides a simpler electronic setup as well as convenient data presentation compared to other URS methods. A common issue for most contact based ultrasonic methods is the sensitivity to coupling variations, which also applies to NBUS. Robustness toward coupling variations and sensitivity to defects were observed to depend on the selection of working frequency and transducer. Since only a single frequency is monitored, careful selection of working frequency and transducer is crucial. This led to the presented theoretical analysis of the performance of different transducer designs and working frequencies in Chapter 4.

1.2 Outline

The outline of the thesis is as follows:

Chapter 2 describes the relationship between NBUS and other URS methods. The principles behind NBUS and the measurement setup are explained.

Chapter 3 introduces two useful models for transducer design and evaluation, a one-dimensional approximation using a transfer matrix model of an electrical network analogue, and a finite element analysis (FEA) model. An interface layer concept is suggested to model kissing bond defects for the purpose of optimizing transducer design.

Chapter 4 summarizes the most important conclusions from Paper I and II. Transducer sensitivity and robustness is discussed by examining standing wave patterns. A practical approach to calculate the efficiency of a transducer for a certain setup is introduced.

Chapter 5 gives an overview of the measurement setup, such as electronics, transducer suspension, and couplant. The steps required to set up the NBUS instrument are explained.

Chapter 6 shows some examples of NBUS applications, such as inspection of CFRP:s and multilayered structures.

1.3 Main Contributions & Included Papers

NBUS is a NDT technique used in the industry, which has received very little attention in the literature. This thesis and the included articles intend to bridge the gap between practice and theory by explaining the principles of NBUS and demonstrating some of its applications. The author is not aware of any similar published work.

The main contribution of this work is the study of the performance of a range of transducer designs on imperfect bonds using simulation. The performance in terms of sensitivity and robustness is analyzed and explained theoretically resulting in design guidelines.

Further contributions include the demonstration of successful use of NBUS for the inspection of CFRP panels.

The thesis comprises the following papers:

I M. Engholm, T. Stepinski. Designing and evaluating transducers for narrowband ultrasonic spectroscopy. *To be published in NDT&E International.*

II M. Engholm, T. Stepinski. Designing and evaluating transducers for narrowband ultrasonic spectroscopy. *2005 IEEE Ultrasonic Symposium*, vol. 4, pp. 2085-8, 2005.

III T. Stepinski, M. Jonsson. Narrowband ultrasonic spectroscopy for NDE of layered structures. *Insight*, vol. 47, no. 4, pp. 220-5, 2005.

IV T. Stepinski, M. Jonsson, Narrowband ultrasonic spectroscopy for NDE of layered structures, *presented at the 16th World Congress of NDT*, 30th August - 3rd September 2004, Montreal, Canada.

The author's contributions to the included papers are:

I Major part of the theoretical work, simulations and conclusions.

II Major part of the theoretical work, simulations and conclusions.

III Modelling, simulations and measurements.

IV Modelling, simulations and measurements.

Short summary of the included papers:

I Transfer matrix modelling of NBUS setups is introduced. A theoretical analysis of the simulated results in Paper II is presented. The conclusions of the analysis are summarized as transducer design guidelines.

II The performance of different transducer designs is analyzed through simulation.

III The principles of the NBUS technique is explained using the KLM equivalent circuit. Inspections on multilayered structures and CFRP:s with artificial defects are presented.

IV The principles of the NBUS technique is explained. The KLM equivalent circuit is used for simulations and compared to measurements on a free oscillating transducer. Results from inspections on CFRP:s with artificial delaminations and impact defects are presented.

Chapter 2

Background

This chapter is an introduction to the NBUS technique. A short introduction to some common ultrasonic techniques explains their similarities and differences compared to NBUS.

2.1 Ultrasonic Inspection

Ultrasonic acoustic waves have been used for a wide range of applications during the last century, such as medical diagnostics, non-destructive testing (NDT), electrical filters, particle filters, sensors, etc. NDT, and especially medical applications, are to a great extent focused on techniques based on the generation and reception of short pulses, such as pulse-echo measurements. Pulse-echo measurements utilizes an ultrasonic pulse which propagates into the inspected object and is reflected at any discontinuities in the object, as shown to the left in Fig. 2.1. The received echoes are analyzed in the time domain to evaluate the condition of the object. The generation and reception of ultrasound are provided by a transducer.

One of the most commonly used wave types is longitudinal waves, that is, waves where the particle motion is in the direction of the wave propagation. Other techniques used in NDT of solids may involve the use of other wave types, for instance, shear waves, guided waves or surface waves. Besides pulse-echo measurements, through-transmission measurements are very common. Through-transmission inspection uses two transducers, one transmitting and one receiving transducer on opposite sides of the inspected object, as shown to the right in Fig. 2.1.

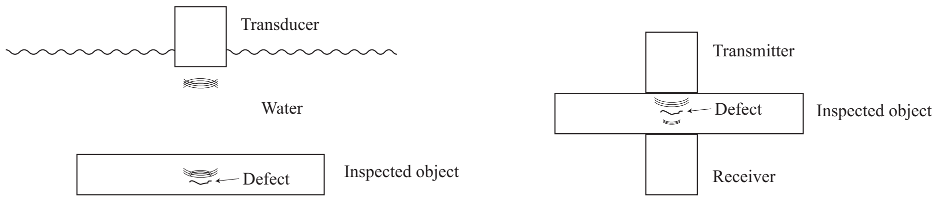

Figure 2.1: Pulse based inspection. Left: pulse-echo inspection. Right: through-transmission inspection.

2.2 Ultrasonic Resonance Spectroscopy

An alternative to the pulse-based methods mentioned in the previous section, where the analysis is performed in the time domain, is ultrasonic resonance spectroscopy (URS). URS is concerned with the extraction of information contained in an object's natural modes of vibration. The resonance frequencies and the corresponding Q-values, that is, the width of the resonance peaks, are parameters which depend on the condition of the material.

Migliori has developed a method called resonant ultrasound spectroscopy (RUS) [1] which utilizes this information, for example, to perform material parameter estimation or NDT. Since analytical expressions relating resonance frequency to material parameters are difficult to find for all but special cases, it is often necessary to use numerical optimization methods to fit the model to the measurement. This issue is addressed in Migliori's work.

URS measurements can be performed using one or more transducers. Using one transducer involves the measurement of the impedance response for a range of frequencies. Multi-transducer setups use one transducer as a transmitter, sweeping through a range of frequencies. The receiving transducer or transducers are then used to acquire a set of spectra that are used to evaluate the object.

Unlike pulse-based tests, that are always performed on a local basis, URS inspection can be performed on either a global or a local basis. Global tests excites the whole object and measures the impedance response for a very broad frequency range through a frequency sweep. The object is excited using a single transducer. For reliable inspection it is required that all important modes of the object are properly excited. This limits the size of the object since it is difficult to fully excite larger objects, due to attenuation and the required excitation energy. The result from the inspection is often a very complicated spectrum, or set of spectra, containing a considerable amount of information about the part. As mentioned previously in this section, a theoretical analysis of the spectra is very difficult for most cases, except for very simple geometries. This method therefore requires other solutions, such as, pattern recognition using a large training set of good and bad parts prior to inspection. Local tests perform the inspection at a certain position of the inspected object. These tests can therefore be applied on larger objects and can be used to localize the defect.

2.3 Narrowband Ultrasonic Spectroscopy

This thesis is focused on narrowband ultrasonic spectroscopy (NBUS), which is a special case of URS. Instead of estimating the properties of certain resonances, the complex valued electrical impedance of a single transducer is measured in a narrow frequency band. The transducer is acoustically coupled to the inspected object through a thin layer of couplant, for example water or oil, see Fig. 2.2. This condition will be called a *coupled system* throughout the thesis. Depending on the object and its condition, the standing wave formed in the transducer and the object will differ. This in turn affects the electrical impedance of the transducer element. Since only a limited volume of the inspected object, in the close vicinity of the transducer, is excited the inspections are local. Typically the operator monitors the measurements by observing the impedance change in the impedance plane between different samples or locations on the inspected object. These measurements are therefore relative, which means that the impedance measured at the inspected area is compared to the impedance corresponding to a reference area, preferably defect free. NBUS also has the advantage of only requiring access to one side of the object. The technique resembles eddy current inspection in some aspects.

The NBUS technique is available in some commercial equipment, for example Olympus NDT's BondMaster[1]. The setup involves selecting a transducer and a working frequency, which is usually set in the vicinity of the transducer's resonance frequency. The BondMaster impedance measurement feature is intended to be used for detecting disbonding in multilayered structures. A disbond is a condition where the adherents are no longer bonded. Our evaluation of the method has shown that the frequency selection is for simple cases, such as disbonding, not crucial since disbonds and voids in structures create major changes in the impedance spectrum. This inspired further investigations to determine the potential of NBUS. As will be explained in Chapter 4, careful selection of transducer and working

[1] BondMaster is a trademark of Olympus NDT

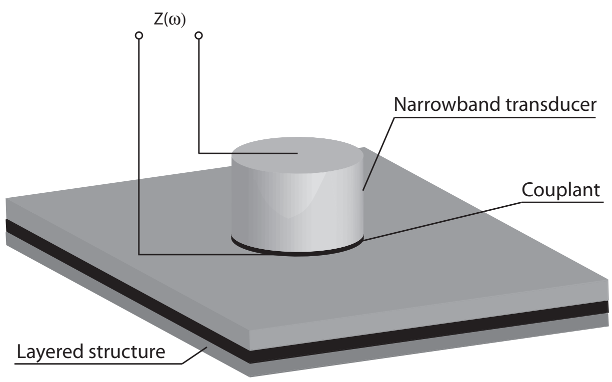

Figure 2.2: Typical NBUS setup (transducer housing and connector are omitted for clarity).

frequency facilitates optimization of the sensitivity of the test setup.

In order to evaluate the possibilities and limitations of NBUS, we have performed measurements on more complicated defects, such as, CFRP panels, cf. Section 6.2, with artificially manufactured defects and aluminium-epoxy structures with weakened bonds, also known as kissing bonds, cf. Section 6.3. Detecting kissing bonds is extremely difficult using standard NDT methods. Our simulations show that great improvements can be achieved in terms of robustness and sensitivity through a proper transducer design and working frequency selection.

It is important when performing demanding inspections that there is a reliable and efficient coupling. This is in practice a limitation for sensitive measurements, since distortion caused by coupling variations makes it difficult to detect the defect. A discussion concerning transducer design with regard to robustness and sensitivity can be found in Papers I and II, and in the summary in Chapter 4.

2.4 Piezoelectric Transducers

An electromechanical transducer is required for the generation and reception of ultrasound. The electromechanical transducer converts electrical energy to mechanical energy and vice versa. The most common way to generate and detect ultrasound is by using transducers built around a piezoelectric element. Piezoelectric materials are a special kind of anisotropic materials where an applied electric field causes contraction or expansion of the material depending on polarity. One of the most common types of piezoelectric materials are ceramics, such as the widely used lead zirconate titanate (PZT).

Piezoelectric elements are manufactured for different types of applications with different geometries (e.g. discs, tubes or cylinders) and polarizations. Piezoelectricity can be found in nature in certain crystals, such as quartz. For manufactured piezoelectric ceramics, a poling process is necessary to produce materials with good electromechanical properties. The poling is performed on the elements at high temperatures by applying an electric field to align the dipoles in the desired direction.

There are several important properties of piezoelectric elements that need to be taken into account when selecting an appropriate element. Basic properties of the piezoelectric material obviously affect the performance of the transducer. Among the electromechanical properties the electromechanical coupling coefficient is a measure of the efficiency of the energy conversion. Mechanical quality factor is a measure of mechanical loss in the element, which in turn affects the sharpness of the resonance peak. Other properties include temperature dependence and dielectric permittivity. When a suitable material has been selected a proper geometric dimension of the element has to be chosen. For elements used for the generation and reception of longitudinal wave motion the thickness of the transducer is important, since it determines the resonance frequency of the thickness mode. The thickness mode is characterized by having most of the motion in the element normal to the front and back surfaces of the disc. The ratio between the thickness and the diameter needs special attention since overtones from lower frequency radial resonances can severely affect the efficiency and resonance frequency of the thickness mode.

Transducers used in ultrasonic applications, for example pulse-echo inspection, are usually designed to have high bandwidth. The reason is that a short acoustic pulse is required for high resolution in the time domain. It is therefore common practice to use a high attenuating backing material at the back surface of the transducer element. Its purpose is to reduce the amount of energy reflecting from the back surface of the transducer back into the element causing it to resonate. Another issue is acoustic impedance miss-match between the transducer's element and the material it is mechanically coupled to, which leads to inefficient energy transmission. To optimize the energy transmission, one or more matching layers can be placed at the front surface of the transducer. A sketch illustrating a typical pulse-echo transducer is shown to the left in Fig. 2.3.

NBUS has different requirements concerning the design of the transducers. To achieve high sensitivity it is necessary to produce a strong resonance

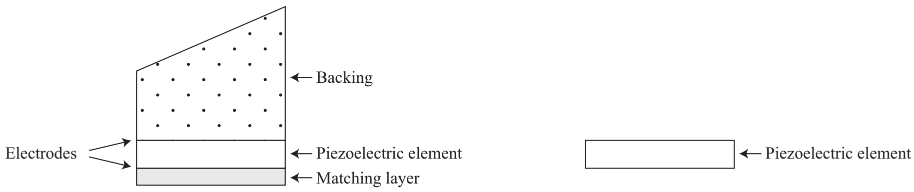

Figure 2.3: Left: traditional transducer design for pulse-echo measurements. Right: transducer design for NBUS

in the coupled system. For this reason narrowband transducers is preferred. Backing is obviously not desired for narrowband transducers where resonance is the preferred state during measurement.

Chapter 3

Theory

This chapter introduces the two models of the NBUS setup used in this work. The presentation intends to give the necessary theoretical material to perform simulations and optimizations of NBUS setups. The theoretical analysis exclusively deals with the inspection of multilayered isotropic elastic structures. The literature on mechanical waves in elastic solids is extensive, including work by Kino [2], Auld [3] and Rosenbaum [4], which have all been used as references in this work.

NBUS relies on harmonic excitation using longitudinal acoustic waves. The one-dimensional approximative transfer matrix model presented here is derived assuming that there is no transversal motion in either the transducer or the object. Possible influence from radial modes in the transducer or other wave types generated at the interfaces such as shear, guided or Rayleigh waves is modeled in the FEA, which can therefore be used as a reference model.

3.1 Elastic Materials

3.1.1 Stress and strain

The stress T is defined as the force F per unit area. In this analysis the main concern is stress perpendicular to the cross-sectional area A of the transducer. The stress and force are related as

$$T = -\frac{F}{A}. \tag{3.1}$$

The strain S is defined as the fractional change in length of a material. For small stresses the relationship between stress and strain can be assumed to be linear. This relationship is known as *Hooke's law*,

$$T = cS, \tag{3.2}$$

where c is the elastic constant of the material.

3.1.2 Energy

The total energy per unit volume is the sum of the elastic energy density and the kinetic energy density [2]. The elastic energy density is calculated as

$$W_c = \frac{1}{4}\Re(TS^*) = \frac{1}{4}\Re\left(TT^*/c\right), \tag{3.3}$$

where $\Re$ denotes the real part and * denotes the complex conjugate. The kinetic energy density is

$$W_v = \frac{1}{4}\Re(\rho v v^*), \tag{3.4}$$

where ρ is the density of the material and v is the particle velocity. The total mechanical energy density is the sum of the terms,

$$W_a = W_c + W_v = \frac{1}{4}\Re(\rho v v^* + TT^*/c). \tag{3.5}$$

In Section 3.2, a transfer matrix model is presented that can be used to calculate stress and particle velocity at an arbitrary point in the object.

3.2 Models of piezoelectric and elastic materials

In this section two general models for the purpose of simulating NBUS inspections are presented. The general setup is illustrated in Fig. 3.1, where a transducer is coupled to a structure, having an arbitrary number of layers, through a layer of couplant.

3.2.1 Parameter Accuracy

Accurate modelling of piezoelectric elements is a complicated topic, especially since it requires accurate estimates of material properties. Due to the nature of the manufacturing process of piezoelectric materials, buying off-the-shelf elements from different batches can result in elements with considerably different parameter values; this can also be the case for samples

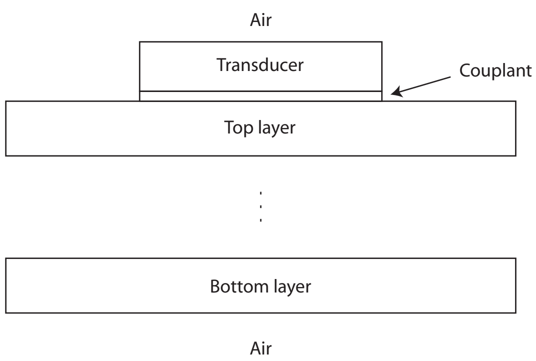

Figure 3.1: General NBUS setup.

within the same batch. Because of this, manufacturers specify properties with tolerances up to 10%. The properties are also affected by the geometry of the element which can further increase the tolerances. This uncertainty is an issue when modelling. For the purpose of optimization, where properties such as resonance frequency and geometry are to be optimized, it is necessary to rely on the properties supplied by the manufacturer.

3.2.2 Transfer Matrix Model

There are several modelling approaches that are feasible for analyzing the performance of a piezoelectric transducer. A thin disc transducer operating in thickness mode can in the ideal case be modeled using a one-dimensional approximation describing the behavior of the transducer for different loads and frequencies. The validity of this approximation depends on the ratio between the diameter and the thickness of the element. For elements with a low ratio this approximation might not hold, because coupling to overtones of other resonances modes can affect the resonance frequency and reduce the efficiency of the transducer. Assuming that this approximation is valid, the model presented below provides a simple and intuitive approach to NBUS modelling. The ratio is not an issue for the accuracy of FEA since it is possible to implement a complete full dimensional anisotropic model of the piezoelectric element, cf Section 3.2.3.

The acoustic variables of the piezoelectric and elastic materials can be represented using electrical analogues by treating the stress T as voltage and particle velocity v as current. This leads to the definition of acoustic impedance $Z = -T/v$[1]. A common way to model piezoelectric elements

[1]The symbol Z is used for both electrical and acoustic impedance, which is common

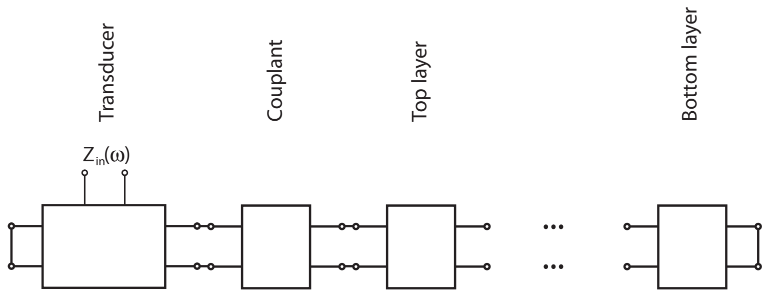

Figure 3.2: Network model of a transducer coupled to a structure.

in one-dimension is to use an equivalent circuit. An equivalent circuit is a model of the transducer consisting of electrical components. Two circuits, one representing the acoustical part and one representing the electrical part is connected through a transformer. Since the electrical and the acoustical part is separated, this type of equivalent circuits can simplify the design of, for example, driving electronics or acoustical matching layers. Two well known equivalent circuit models are the Mason model [5] and the KLM model [6]. Both models are derived based on the same assumptions and yield comparable end results [7].

Instead of using equivalent circuits, a transducer coupled to a multilayered structure can be modelled using a network representation of the piezoelectric element in the transducer and the elastic layers of the structure. This representation produces comparable results to the equivalent circuits. Which one to use is a matter of convenience. The transfer matrix model is used in this work.

Fig. 3.2 shows a network modelling the general NBUS setup from Fig. 3.1. The piezoelectric element is represented with a three-port network, having two acoustic inputs and one electric input. The couplant and each layer in the inspected structure is represented with a two-port network, having two acoustic inputs. As mentioned in section 2.4, NBUS transducers typically lacks backing. The back side of the transducer is therefore approximately terminated with a short circuit, since the characteristic impedance of air is very small compared to the characteristic impedance of the transducer. The same applies for the bottom of the inspected structure.

The piezoelectric element is shown in the left illustration of Fig. 3.3, and the corresponding network representation to the right. The network has two acoustic inputs located on the sides of the box, and one electric input located

in the literature.

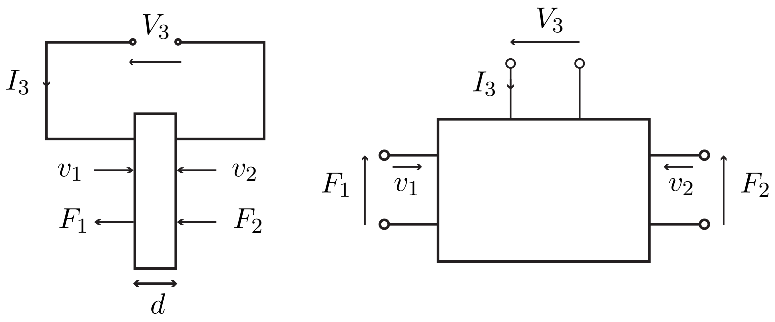

Figure 3.3: Left: the physical transducer. Right: the transducer as a three-port network.

on the top of the box. The following expressions are derived in the same manner as in [2]. The definitions of the piezoelectric constants can be found in the referred textbooks. Material data for standard test specimens are typically supplied by the manufacturer of the piezoelectric material.

The force $F_{1,2}$ and voltage V_3 are related to the particle velocity $v_{1,2}$ and current I_3 as

$$\begin{bmatrix} F_1 \\ F_2 \\ V_3 \end{bmatrix} = -j \begin{bmatrix} AZ_0 \cot kd & AZ_0 \csc kd & h_{33}/\omega \\ AZ_0 \csc kd & AZ_0 \cot kd & h_{33}/\omega \\ h_{33}/\omega & h_{33}/\omega & 1/\omega C_0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ I_3 \end{bmatrix}, \tag{3.6}$$

where k is the acoustic wave number, ω is the excitation frequency, Z_0 the characteristic impedance, d the thickness of the transducer, and h_{33} the transmitting constant in the longitudinal direction.

The input impedance on port 1, that is, the back surface of the transducer, is labeled Z_B, where $Z_B = F_1/v_1$. For port 2, the front surface, the input impedance is labeled Z_A, where $Z_A = F_2/v_2$.

The acoustic wave number k is defined as

$$k = \sqrt{\frac{\rho}{c_{33}^D}}\omega, \tag{3.7}$$

where ρ is the density of the material and c_{33}^D is the complex stiffened elastic constant in the longitudinal direction under uniform electric displacement. The characteristic impedance is defined as

$$Z_0 = \sqrt{\rho c_{33}^D}. \tag{3.8}$$

The capacitance of the element is $C_0 = \epsilon_{33}^S A/d$, where ϵ_{33}^S is the permittivity under zero strain.

The elements in matrix (3.6) are labelled as follows

$$\begin{bmatrix} F_1 \\ F_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ I_3 \end{bmatrix}. \tag{3.9}$$

Noting that the matrix in Eq. (3.6) is symmetric, the electrical input impedance $Z_{in}(\omega)$ can be calculated with simple algebra as

$$Z_{in} = \frac{V_3}{I_3} = Z_{33} - \frac{Z_{13}^2(Z_A + Z_{22}) + Z_{23}^2(Z_B + Z_{11}) - 2Z_{12}Z_{13}Z_{23}}{(Z_A + Z_{22})(Z_B + Z_{11}) - Z_{12}^2}. \tag{3.10}$$

The non-piezoelectric elastic materials, shown in the right illustration of Fig. 3.4, and the corresponding network representation, shown to the right.

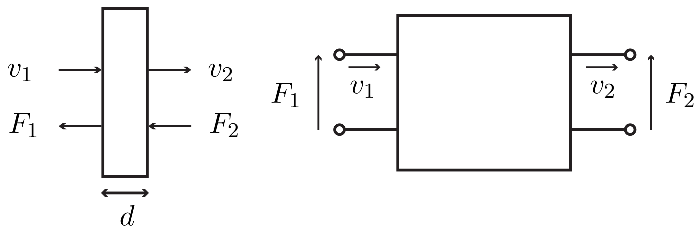

Figure 3.4: Left: a layer of elastic material. Right: the corresponding two-port network representation.

The transfer matrix for non-piezoelectric materials can be derived in the same manner as Eq. (3.6),

$$\begin{bmatrix} F_2 \\ v_2 \end{bmatrix} = \begin{bmatrix} \cos kd & -jAZ_0 \sin kd \\ -j \sin kd/AZ_0 & \cos kd \end{bmatrix} \begin{bmatrix} F_1 \\ v_1 \end{bmatrix}. \tag{3.11}$$

The elements of the matrix in (3.11) are labelled as

$$\begin{bmatrix} Z_{11}^a & Z_{12}^a \\ Z_{21}^a & Z_{22}^a, \end{bmatrix}.$$

The input impedance Z_1 on port 1 of the elastic layer is

$$Z_1 = \frac{Z_{12}^a + Z_{22}^a Z_2}{Z_{21}^a Z_2 + Z_{11}^a}, \tag{3.12}$$

where $Z_2 = F_2/v_2$ is the impedance on port 2. The input impedance of a multilayered structure can thus be calculated in a recursive manner. Starting at the bottom layer of the structure, repeated use of Eq. 3.12 gives the input impedance of the top layer.

3.2.3 Finite Element Analysis

Since the transfer matrix model is based on the assumption that the transducer and the structure is one-dimensional, it is convenient to use a more accurate model to verify that the approximation is reasonable for the purpose. The cost of using such a model comes mainly from increased computational time and from reduced transparency. Finite element analysis (FEA) can provide a highly accurate model of the setup, including multiple vibrational modes, multiple wave types (e.g. shear and guided waves), acoustic pressure modelling of liquid coupling layer etc. The FEA model presented in this section is used in Paper I and II as a reference model to verify the conclusions drawn from the one-dimensional model.

NBUS inspections are commonly carried out on objects of large lateral extent, that is, objects having a lateral size of several times the diameter of the transducer element. Since the simulations are intended to be as general as possible, effects caused by limited lateral extent of the object has to be seen as special cases. Therefore it is reasonable to assume that the inspected object is laterally infinite. Instead of using a model of very large lateral extent to model this, and thereby increasing the required computation time, it is more efficient to terminate the lateral boundaries with a perfectly matched layer (PML). A PML is designed to absorb all incident waves entering the layer.

Since the piezoelectric elements used in NBUS transducers usually are circularly shaped discs and the inspected structure is considered as laterally infinite in extent, the setup can be modeled as axi-symmetric. This further reduces the required computational power.

The model used in this work was created and solved using the Comsol Multiphysics[2] modelling package. An example of a model geometry is shown in Fig. 3.5. It shows a piezoelectric element (Pz27[3]) coupled to a structure through a thin layer of couplant. The structure consists of two adhesively bounded aluminium plates.

The uncertainty in the material properties of the piezoelectric element mentioned earlier is a considerable problem for FEA. Since the model of

[2] Multiphysics is the trademark of COMSOL, Inc.
[3] Pz27 is manufactured by Ferroperm Piezoceramics A/S.

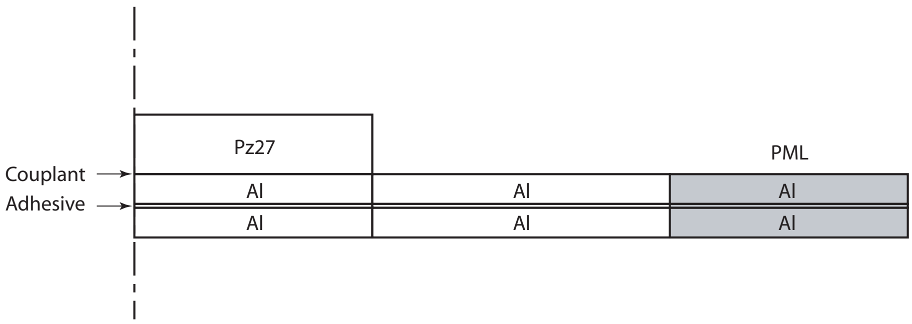

Figure 3.5: Example of the geometry of a FEA model.

the piezoelectric element has 12 independent variables, neglecting loss and the geometry of the element, it makes parameter estimation for FEA much more complicated than for the one-dimensional approximation, with only four parameters. If loss is to be included in the model, many of these parameters have to be complex, further increasing the complexity.

3.3 Modelling the Imperfect Interface

As will be discussed in Section 6.3, detecting kissing bonds is far from a trivial problem. To be able to make a theoretical analysis of the performance of different transducers in terms of sensitivity to kissing bonds and robustness towards coupling conditions, a model for kissing bonds was required. Jiao and Rose proposed a model for imperfect interfaces [8] using an interface layer. Instead of attempting to model and estimate all possible conditions of an imperfect bond, the interface condition is represented by a thin interface layer with a set of material properties different from those of the adherent and the adhesive. The interface layer is perfectly bonded on both sides. Details concerning the concept of interface layers to model kissing bonds, a performance analysis of different transducers and the following conclusions can be found in Paper I and II.

3.4 Loss

To produce reasonable simulation results in terms of resonance peak amplitude and width it is necessary to include loss in the model. Elastic materials exhibit mechanical loss due to a number of factors. Piezoelectric materials are, besides mechanical loss, also subjected to dielectric and piezoelectric losses. Modelling of loss using accurate loss coefficients over a wide frequency range is complicated since different loss mechanisms are prominent in different frequency ranges. A simplified loss model has been used in this work using frequency independent complex material constants. Elastic and dielectric losses are included in the models and are defined as,

$$c = c_{real}(1 + j \tan \delta_c) \tag{3.13}$$
$$\epsilon^S = \epsilon^S_{real}(1 - j \tan \delta_\epsilon), \tag{3.14}$$

where ϵ^S is the permittivity under zero strain, $\tan \delta_c$ and $\tan \delta_\epsilon$ are the mechanical and the dielectric loss tangent, respectively. c_{real} and ϵ^S_{real} are the lossless elasticity and permittivity, respectively.

For the FEA, the set of loss tangents is, for the general case, increased to include individual tangents for the full set of elastic and dielectric coefficients. In this work, due to limited knowledge of parameter data, the loss tangents are assumed to be equal for all the elastic and dielectric coefficients, respectively.

Chapter 4

Optimizing Sensitivity and Robustness

This chapter summarizes the conclusions from Papers I and II. The sensitivity and the robustness of the measurements can be explained by two factors, the effective electromechanical coupling coefficient (EMCC) and the shape of the standing wave pattern formed in the coupled system.

4.1 Electromechanical Coupling Coefficient

One of the two important factors when evaluating transducers and piezoelectric elements is the effective electromechanical coupling coefficient (EMCC) k_{eff}. The EMCC is a measure of the efficiency of the energy conversion in the piezoelectric element. The EMCC is also an important factor for NBUS setups, as will be explained in this section.

The coupling coefficients are defined for two different cases, static and dynamic. The material coupling coefficient is defined under static or quasi-static conditions, which means that the stress is uniform in the element. Since NBUS is concerned with resonances, the dynamic case is of greater interest. There are a number of different methods that can be used to estimate the effective EMCC of a piezoelectric element. The method recommended in the IEEE Standard of Piezoelectricity [9] for the dynamic case, is to measure or to calculate the resonance and the anti-resonance frequencies of the resonator. The resonance and anti-resonance frequencies can be estimated using either of the models presented in Section 3.2. Experimentally the EMCC can be estimated by measuring the frequency response using a network analyzer. The resonance and anti-resonance frequencies of a specific mode is related to the effective coupling factor as [9]

$$k_{eff}^2 = \frac{f_p^2 - f_s^2}{f_p^2}, \tag{4.1}$$

where f_p is the frequency of maximum resistance (antiresonance) and f_s is the frequency of maximum conductance (resonance). This formula gives the EMCC for a frequency that is the arithmetic mean of the resonance and the anti-resonance frequency. A summary and an analysis of different methods to calculate the EMCC can be found in a paper by Chang *et al.* [10].

The first conclusion drawn from the simulation results in Paper I is that to achieve maximum sensitivity during a measurement, it is necessary to work with the coupled system in resonance. Contrary to the recommendations of selecting the transducers resonance frequency as a working frequency, this states that it is more efficient to work with the coupled system in resonance. If the transducer coupled to the inspected object is regarded as a resonator, then the effective EMCC indicates the sensitivity that can be expected from the measurement.

4.2 Standing Wave Patterns

The sensitivity toward changes in the material properties of the inspected object also depends on the distribution of elastic and kinetic energy. By examining Eq. (3.5) it can be concluded that changes in density affect the kinetic energy while changes in the elastic constant affect the elastic energy. For lossless materials the total energy density is constant in each layer, making the sum of elastic energy and kinetic energy constant.

The kinetic and the elastic energy distribution can be calculated using the standing wave patterns of the stress and the particle velocity for a certain resonance frequency. The standing wave pattern is a vibrational pattern caused by interference between incident and reflected waves. The standing wave patterns can be calculated using the models presented in Section 3.2.

The second conclusion drawn from the simulation results in Paper I is that the energy distribution has some interesting implications on the performance of the measurement. By examining the simulated standing wave pattern it is possible to draw conclusions about the efficiency of the transducer to certain defects. The most important conclusion made from these simulations is that having a stress minimum, i.e. a minimal amount of elastic energy, in the coupling layer minimizes the sensitivity to thickness changes

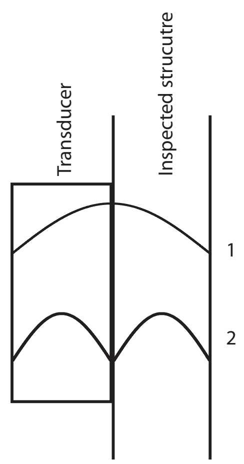

Figure 4.1: Standing wave pattern of the stress for the two lowest resonance frequencies. Resonance 1 is the half-wave resonance and resonance 2 is the full-wave resonance. The amplitude of the stress at a particular position indicates the sensitivity that can be expected to variations in thickness and elasticity.

in the couplant, which is of course desired. Fig. 4.1 is a sketch of two wave patterns as an example of both the worst (resonance 1) and the best (resonance 2) case of standing wave patterns. The stress is naturally zero at the edges. Resonance 1 has a stress maximum in the coupling layer, which results in a high sensitivity to thickness changes in the couplant. Resonance 2 on the other hand, has a stress minimum in the coupling layer, at which it is zero if there is no loss, and is therefore more robust to couplant variations.

This makes it possible to control the sensitivity to certain parameters. Placing a stress node in a certain position decreases the sensitivity to elasticity changes and at the same time increases the sensitivity to density changes, while an anti-node gives the opposite result. Looking back at resonance 2 in Fig. 4.1 shows that the center of the inspected object is where maximum sensitivity to elasticity changes is expected.

Chapter 5

Measurement Setup

This chapter describes the measurement setup used in this work in terms of electrical setup, transducer mounting and mechanized inspection. The most important steps concerning the setup of the NBUS instrument are explained.

5.1 Electric Circuit

An overview of the electrical circuit used for the measurements is shown in Fig. 5.1. To improve the robustness and sensitivity of the measurements it is possible to use two identical transducers for differential measurements. Although not thoroughly investigated, differential measurements are expected to, for example, increase the sensitivity and reduce drift caused by heating of the piezoelectric element. Differential measurements have been used for the results presented in Chapter 6. The bridge is driven by a sinusoidal signal, $u(\omega)$, where ω is the selected working frequency. The bridge is connected to a differential input gain stage and is then fed into a lock-in amplifier to demodulate the signal. The two components of the lock-in amplifier output are displayed in an impedance plane plot.

5.2 Transducer Mounting

As mentioned in Section 2.3, coupling variations is a limiting factor when performing demanding inspections. Optimizing the transducer design and the selection of working frequency, as discussed in Chapter 4, is only one part of the problem. An inadequate transducer mounting can severely reduce the sensitivity of the measurements. Two different transducer mountings,

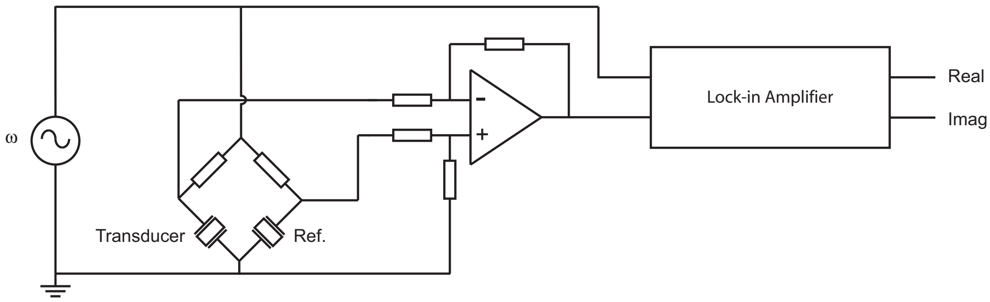

Figure 5.1: Schematic of an electrical circuit to use for NBUS inspection. The transducer used as a probe is labeled Transducer and the reference transducer is labeled Ref.

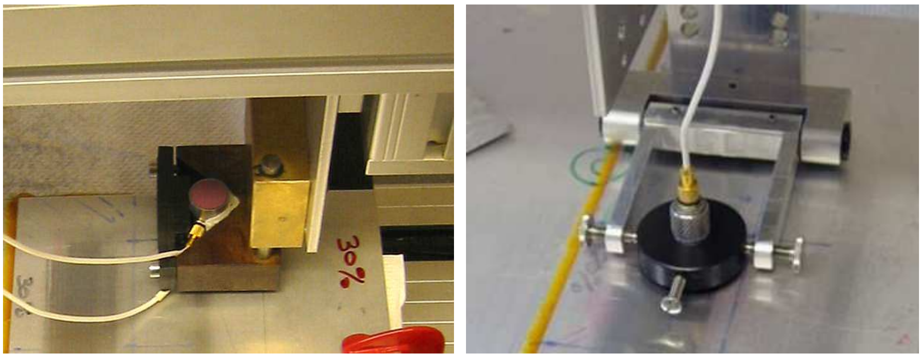

Figure 5.2: The two evaluated transducer suspensions.

shown in Fig. 5.2, were therefore evaluated. The leftmost is suspended by two springs pushing the transducer down towards the object. The disadvantage observed with this mounting was the difficulty to produce replicable conditions.

The rightmost mounting consisted of a kind of sled with soft springs pushing the transducer down. The transducer is free to move in all directions and thereby following possible variations of the inspected surface. Better reproducibility was achieved using this mounting.

5.3 Mechanized Inspection

Inspection using NBUS is usually performed by manually moving the transducer over the inspected surface. To evaluate different transducers and setups it was necessary to enhance reproducibility and to control the trans-

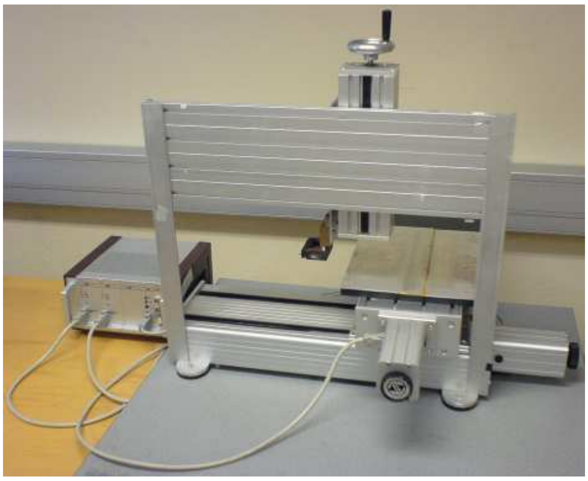

Figure 5.3: XY-scanner used for mechanized inspection.

ducer's position. For this purpose a computer controlled XY-scanner was used as seen in Fig. 5.3.

5.4 NBUS Instrument Setup

For inspections requiring high sensitivity, it is crucial that the equipment is set up properly. As explained in Chapter 4, simulation can be valuable during setup. By analyzing the modes of the coupled system, the sensitivity and robustness can be optimized by selecting the appropriate transducer and working frequency.

Another valuable tool when setting up an inspection is a network analyzer. By examining the impedance spectrum of the transducer coupled to the inspected object, the resonance frequencies of the system can be determined. This approach provides less information concerning transducer selection and design, but can still be feasible when it comes to working frequency selection.

The last step involves configuring the NBUS instrument. With the transducer coupled to the inspected object, the cursor on the instrument display is set to the origin of the complex impedance plane. Relative changes of the impedance is now shown on the instrument's impedance plot as deviations from the origin. While moving the transducer over the object, the amplification of instrument is set as high as possible without saturating the instrument's amplifiers.

Chapter 6

Applications

In this chapter a selection of the evaluated applications of NBUS that was carried out during this work is presented. Besides standard bond testing, examples from inspections of CFRP:s and imperfect bonds are shown.

6.1 Disbonds in Multilayered Structures

The NBUS technique has traditionally been used in the industry for bond testing of multilayered structures. Our own measurements have shown that the method has no difficulty in detecting artificially manufactured disbonds.

The structure used for the evaluation was manufactured by CSM Materialteknik[1]. It is a sample with artificially introduced defects representing a piece of lower wing skin used in Saab's aircrafts Saab 340 and Saab 2000. It consists of three aluminium layers adhesively bonded by a layer of epoxy, as shown in Fig. 6.1. The structure has disbond defects introduced in both the top and the bottom adhesive layer. The results from an NBUS inspection of the object can be seen in Fig. 6.2. The phase is related to the depth of the defect.

6.2 CFRP Panels

The participation in the EU projects INCA and NANOSCAN partly involved evaluation of URS on CFRP:s. Measurements were performed on panels with different types of defects, for example, teflon insertion and im-

[1] CSM Materialteknik i Linköping, now Bodycote CSM

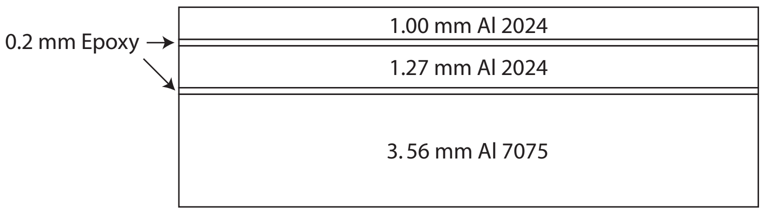

Figure 6.1: The five layers of the lower wing skin sample.

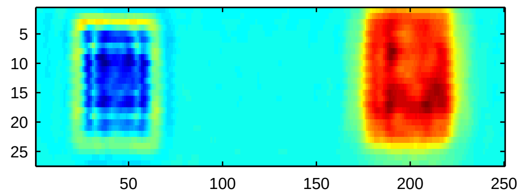

Figure 6.2: Measurement performed on the wing skin sample with defects in top (left) and bottom (right) adhesive layer. Blue and red areas represents impedance changes having different phase.

pact damages. Results from NBUS measurements on CFRPs are presented in Papers III and IV.

Below is a comparison between the performance of a through-transmission C-scan and the corresponding NBUS inspection of the CFRP sample illustrated in Fig. 6.3. The sample consists of five steps with varying thicknesses. Each step has six areas with teflon insertions in the top, center and bottom, simulating disbonding. Fig. 6.4 shows the result from the C-scan performed in through-transmission and Fig. 6.5 the NBUS scan. It is apparent that NBUS performs equally well as the conventional transmission inspection, that requires access to both sides of the sample.

6.3 Kissing bonds

Part of the INCA project was focused on evaluation of the feasibility of ultrasonic resonance spectroscopy to detect a type of defects called kissing bonds.

Common defect types such as disbonds or cracks are for many cases detectable using standard NDT techniques. These defects are what might be considered as gross. Kissing bond is a term used for many different types of

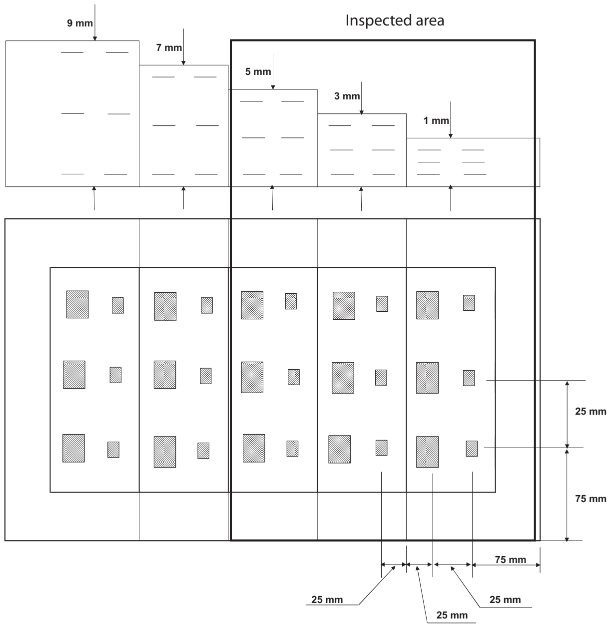

Figure 6.3: CFRP Sample. The side view shows the position of the defects for each layer. In the top view grey areas indicates defect.

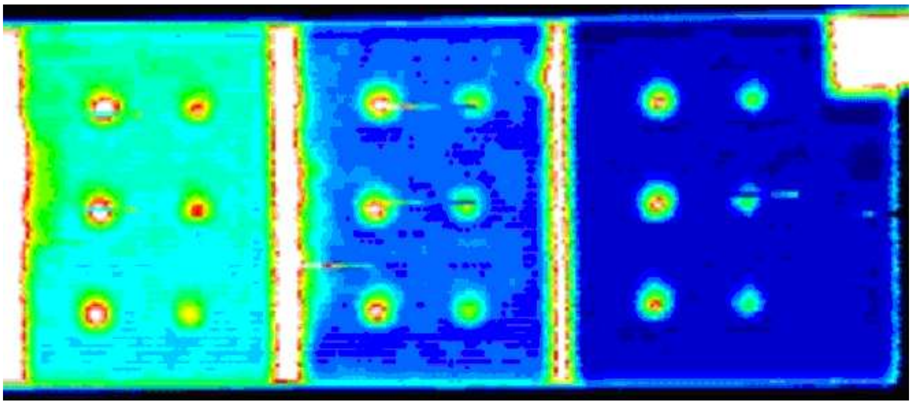

Figure 6.4: Through-transmission C-scan of three steps of the CFRP step sample. The six defects in each of the three layers can be seen as circular highlights.

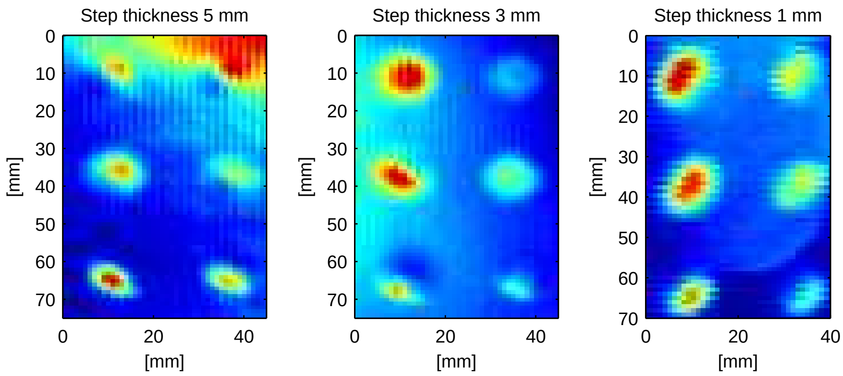

Figure 6.5: NBUS measurement of CFRP step sample. Impedance change is shown in red.

adhesive defects in the literature. Brotherhood *et al.* [11] summarizes some of the literature written on the subject and also examines the detectability of kissing bonds under compressive loading. They define a kissing bond as a disbond where the two surfaces are connected in some way, which includes defects such as slip bonds, imperfect interfaces, etc. Normal incidence 10 MHz focused pulse-echo ultrasound was used in the experiments. They conclude that some contaminations between the adherent and the adhesive, e.g. grease, are detectable, but that a thin layer of release agent, Frekote[2], is not detectable in their setup.

The kissing bond defect samples used in this study were produced by CSM Materialteknik from a set of criteria formulated by CSM:

1. The strength must be below 10-20% of nominal strength (lap shear test).

2. The mode of failure must be interfacial (between adherent and adhesive, e.g. in the primer or anodization layer)

3. Materials introduced must remain at the adherent/adhesive interface and not migrate into either the adherent or the adhesive.

4. The thickness of material introduced must not be $>$ 10% of that of the bond line.

5. The kissing bonds must not be distinguishable from normal bonded joints with conventional NDT technique (C-scan).

[2]Frekote is a registered trademark of Henkel Corporation

Figure 6.6: Lap shear jointed kissing bond samples from side.

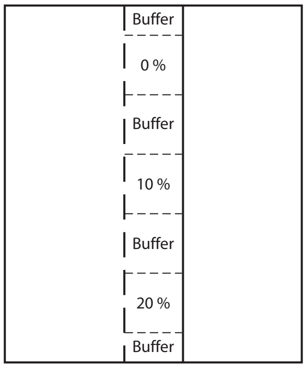

Figure 6.7: Kissing bond sample (view from above) illustrating the different release agent concentrations.

The process chosen for the fabrication of the kissing bonds was chemical surface modification. A thin layer of Frekote was applied between the adherent and the adhesive. The release agent was diluted to different concentrations in a solvent. The process proved to satisfy the criteria.

The samples were manufactured as lap shear jointed aluminium plates as shown in Fig. 6.6. The sample shown in Fig. 6.7 illustrates one of four manufactured samples, each sample having a unique set of Frekote concentration zones.

NBUS has been evaluated using several different transducers and working frequencies, but no transducers have yet been designed using the results presented in the thesis. Although some measurements have been promising, the reproducibility has been a problem. This is likely caused by transducer mounting and coupling variations. The results from one of these measurements are shown in Fig. 6.8. This particular inspection shows a high correlation between the magnitude of the impedance change and the Frekote concentration.

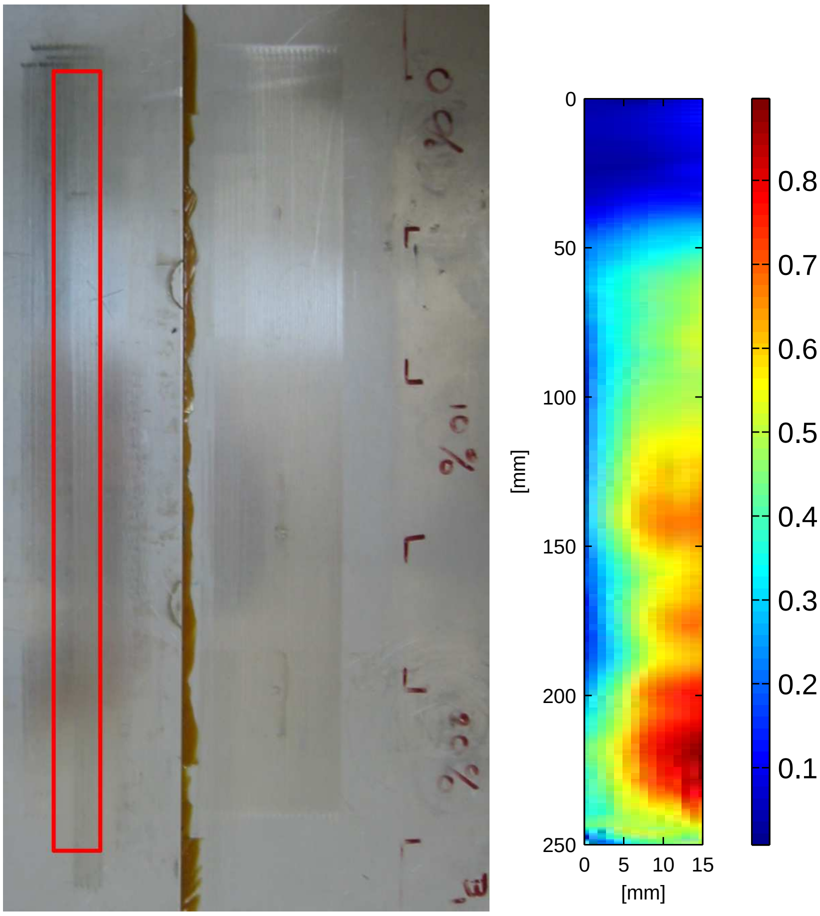

Figure 6.8: Left image shows a kissing-bond sample plate with Frekote concentrations of 0%, 10% and 20%. Between each Frekote zone is a buffer zone with no applied Frekote, although leakage could occur. Right image shows the result from an inspection of the area inside the red rectangle in the left image. The color represents the magnitude of the impedance change.

Chapter 7

Concluding Remarks

This thesis summarizes the main results of the research concerning the development of an improved NBUS technique. NBUS has been explained from both practical and theoretical viewpoints. Two models have been used in the work, an equivalent circuit and a FEA model. The FEA model has been used as a reference model to verify the conclusions made from the analysis of the simplified equivalent circuit model. Transducer performance has been analyzed with regard to sensitivity and robustness. The analysis concludes that the effective electromechanical coupling coefficient (EMCC) is a good measure of the expected performance of a transducer for a certain inspection setup. The importance of the distribution of kinetic and elastic energy is explained using standing wave patterns. It explains the differences in sensitivity in different parts of the coupled system. The results create a solid ground for the development of an efficient transducer design procedure.

Examples of successful use of the NBUS technique to detect different types of defects have been shown.

Chapter 8

Future work

The theoretical analysis and guidelines presented in Papers I and II have not yet been used to design an application specific transducer capable of evaluating the kissing bond samples. Previous evaluations of the detectability of kissing bonds have mainly focused on the experimental setup ignoring known characteristics of the inspected object. For instance - when inspecting potential kissing bonds, it is obvious that the defect is located at an adherent-adhesive interface. Using the model presented in this work makes it possible to efficiently separate coupling variations from actual defects.

Initial investigations using simulations have shown that measuring the impedance at multiple working frequencies could make it possible to distinguish actual defects from setup issues, such as couplant variations. This method, however, needs further development and evaluation.

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Paper I

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Designing and Evaluating Transducers for Narrowband Ultrasonic Spectroscopy

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Abstract

Introduction of new composite materials in aerospace applications has created a demand for an efficient NDE technique. Ultrasonic resonance inspection is especially suitable for the inspection of multilayered structures. In our previous work we have described the principle of narrowband ultrasonic spectroscopy (NBUS), where the surface of an inspected structure is scanned with a resonant transducer whose frequency response is monitored in a narrow frequency band. This paper is concerned with optimizing the NBUS setup consisting of a piezoelectric transducer coupled to a multi-layered structure. Differences in the electrical impedance of a piezoelectric transducer caused by variations of parameters of the inspected structure are estimated using an equivalent circuit model and a finite element analysis. The theoretical analysis presented in the paper results in design guidelines for NBUS transducers.

Key words: Narrowband ultrasonic spectroscopy; Transducer design; Layered materials

1 Introduction

In a broadband ultrasonic resonance spectroscopy (URS) test a frequency spectrum of the inspected object is acquired and an analysis is performed to evaluate material properties and/or to detect flaws. A broadband transducer, weakly coupled to the inspected structure acquires its frequency response in some frequency band where a number of resonances should occur. The resonance frequencies depend on a number of factors, such as, material properties,

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object geometry, temperature, and the presence of flaws in the structure. A transmitting transducer is excited by a swept frequency signal and the spectrum is acquired using a number of receiving transducers. Changes in the condition of the structure will influence the position of the resonances in the frequency response which enables making a diagnosis using a specific pattern recognition method adopted for this purpose.

Narrowband ultrasonic spectroscopy (NBUS) is based on a slightly different approach to URS. NBUS operates on the principle of monitoring the electrical impedance at a certain frequency, the working frequency, of a piezoelectric probe coupled to the inspected multilayered structure. Since a piezoelectric transducer is an electromechanical device the properties of its electrical resonance depend on its mechanical load, i.e., the acoustic impedance of the inspected material. Thus, in this kind of test, the resonance spectrum of the inspected structure is not measured directly but through its influence on the resonance spectrum of a narrowband transducer. A feasible way of extracting information about the inspected structure using a narrowband piezoelectric transducer is sensing variations of its electrical impedance caused by the varying conditions of the inspected structure. The electrical impedance for a predefined frequency in the vicinity of the transducer's resonance is relatively easy to measure using a vector voltmeter.

Changes in the multilayered structure, e.g. disbonds or imperfections in the interface between the adherent and the adhesive (e.g. *"kissing bond"*) will change the acoustic impedance at the front side of the probe coupled to the structure. This will result in a change of its spectrum, which will be pronounced at certain frequency bands depending on the transducer, the structure, and the type of flaw. Selecting an appropriate transducer and an appropriate working frequency are the two most important choices when using NBUS.

It has been proven that the NBUS method is capable of detecting both artificial delaminations in multilayered aluminium structures as well as artificial delaminations and impact defects in carbon fiber reinforced composites [1]. A few instruments utilizing this principle are commercially available, e.g. the BondMaster from *Olympus NDT*.

In practical use of the NBUS technique, the working frequency is selected *ad hoc*, based on manufacturer recommendations and user experience. The nominal probe resonance frequency in air recommended by manufacturers is not necessarily a bad choice, but since a transducer's impedance changes considerably when coupled to the inspected structure a substantial room for better selections exists. Our aim is to provide users with guidelines for transducer selection based on theoretical analysis of the joint frequency response of the NBUS setup consisting of the inspected structure and the transducer.

We have explained the NBUS principle and presented some of its applications in our previous publications, [1], [2]. Here, we use use simulation results to explain some interesting features of this method and to formulate guidelines for designing NBUS transducers. For this purpose we examine a setup consisting of a transducer and two bonded aluminum plates. A one-dimensional transducer model is used for the analysis and the obtained results are verified using finite element analysis (FEA). As an evaluation case we introduce an imperfect bond between the aluminium plate and the adhesive layer. An interface layer is used to model the imperfect bond and to enable comparison of the performance of different transducers and working frequencies through simulation.

One of the major problems with NBUS is its sensitivity to coupling. We address this issue and show how to decrease the influence of coupling, while maintaining a high sensitivity to defects. Although this work focuses mainly on NBUS inspections, it can also be used to extract interesting features from impedance responses of contact broadband ultrasonic spectroscopy.

2 Theoretical background

2.1 Setup

A typical NBUS setup, which is also used in this work, is shown in Fig. 1. An ultrasonic transducer made of piezoelectric material is placed at the surface of the inspected structure. A high quality acoustic coupling between the transducer and the structure must be provided. The transducer impedance variations measured at a selected working frequency are influenced by the state of the inspected structure and the acoustic coupling. Unlike pulse-echo ultrasonic inspections, narrowband transducers are preferred for NBUS measurements since sharp resonance peaks result in higher sensitivity, provided a proper working frequency is chosen. This section covers the theory needed for

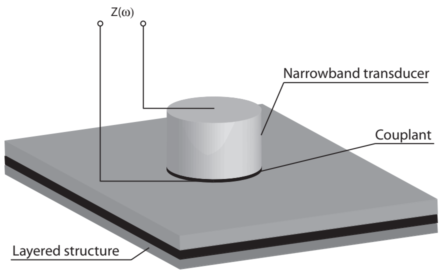

Fig. 1. NBUS inspection of layered structure

the implementation of the one-dimensional model. A more thorough explanation of the implementation can be found in Wilcox *et al.* [3], which has served as an inspiration to this section.

2.2 Transfer matrices

The NBUS transducers considered here are designed to operate with longitudinal waves along the z-axis. To simplify the analysis the transducers are assumed to have no transversal movement. In the same manner as, for instance, Kino [4], the transducer is treated as a three-port electrical network shown in Fig. 2 with two acoustic ports (sides) and one electrical port (top). This model is intuitively understandable and much more transparent than, for example, a three-dimensional anisotropic FEA.

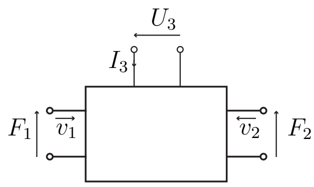

Fig. 2. Three-port network representation of piezoelectric medium

The force F on an acoustic port are related to the stress T and the area A of the transducer as:

$$F = -AT \tag{1}$$

The force $F_{1,2}$ and voltage V_3 are related to the particle velocity $v_{1,2}$ and current I_3 as:

$$\begin{bmatrix} F_1 \\ F_2 \\ V_3 \end{bmatrix} = -j \begin{bmatrix} AZ_0 \cot kd & AZ_0 \csc kd & h_{33}/\omega \\ AZ_0 \csc kd & AZ_0 \cot kd & h_{33}/\omega \\ h_{33}/\omega & h_{33}/\omega & 1/\omega C_0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ I_3 \end{bmatrix} \tag{2}$$

where k is the acoustic wave number, Z_0 the characteristic impedance, d the thickness of the transducer, and h_{33} the transmitting constant in the longitudinal direction. The acoustic wave number k is defined as:

$$k = \sqrt{\frac{\rho}{\bar{c}_{33}^D}}\omega \tag{3}$$

where ρ is the density of the material and $\bar{c}_{33}^D$ is the complex stiffened elastic constant along the z-axis under uniform electric displacement. Elastic loss is accounted for by a complex term in the elastic constant:

$$\bar{c}_{33}^D = c_{33}^D(1 + j\frac{1}{Q_m}) \tag{4}$$

where Q_m is the mechanical quality factor. The characteristic impedance is defined as $Z_0 = \sqrt{\rho \bar{c}_{33}^D}$, and the capacitance is $C_0 = \frac{\epsilon_{33}^S A}{d}$ where ϵ_{33}^S is the permittivity under zero strain. Including dielectric losses gives complex permittivity $\bar{\epsilon}_{33}^S = \epsilon_{33}^S(1 - j\tan\delta)$ where $\tan\delta$ is the dielectric dissipation factor.

Non-piezoelectric elastic material can be considered as a two-port network by treating force F the same way as voltage and particle velocity v as current as shown in Fig. 3. The transfer matrix for non-piezoelectric materials can be derived in the same manner as Eq. (2):

$$\begin{bmatrix} F_2 \\ v_2 \end{bmatrix} = \begin{bmatrix} \cos kd & -jAZ_0 \sin kd \\ -j \sin kd / AZ_0 & \cos kd \end{bmatrix} \begin{bmatrix} F_1 \\ v_1 \end{bmatrix} \tag{5}$$

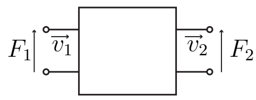

Fig. 3. Two port network representation of elastic medium

2.3 Energy

Generally, relationships (2) and (5) enable calculating the force and particle velocity at an arbitrary point in the structure. The total energy per unit volume is the sum of the elastic energy density and the kinetic energy density [4]. The elastic energy density:

$$W_c = \frac{1}{4}\Re(TS^*) = \frac{1}{4}\Re\left(TT^*/c\right) \tag{6}$$

where $\Re$ denotes the real part, T the stress, S the strain and c the elastic constant of the material. The stress and strain are related by Hooke's law:

$$T = c(1 + j\alpha)S \tag{7}$$

where $c(1 + j\alpha)$ is the complex elasticity constant and α is the attenuation factor. The kinetic energy density:

$$W_v = \frac{1}{4}\Re(\rho v v^*) \tag{8}$$

where ρ is the density of the material. Total mechanical energy density in the structure is a sum of both terms:

$$W_a = W_c + W_v = \frac{1}{4}\Re(\rho v v^* + TT^*/c) \tag{9}$$

We will use the effective coupling factor k_{eff} as a measure of the efficiency of the electromechanical energy conversion. The effective coupling factor is defined as [5]:

$$k_{eff}^2 = \frac{f_p^2 - f_s^2}{f_p^2} \tag{10}$$

where f_p is the frequency of maximum resistance (anti-resonance) and f_s is the frequency of maximum conductance (resonance).

3 Modeling

It should be clear that our aim here does not consist in creating a perfect model of the physical setup with tuned accurate parameters. We intend to present an approach that can be used when designing NBUS transducers to determine at which working frequencies the detection of specific defects is most likely. This approach should enable designing application specific transducers for applications where standard transducers used in pulse-echo mode yield poor results, for example, for the detection of imperfect bonds.

Two different models have been used in this work: a one-dimensional transfer matrix model for most of the results presented, and an axi-symmetric finite element model to verify the conclusions drawn from the simplified model. Both models are used to calculate the electrical input admittance of the transducer coupled to the inspected structure.

The transducer transfer matrix model used here was presented in detail in Section 2.2. It has the form of an electromechanical three-port network with an electrical port and two acoustic ports: the front and back of the transducer. Since only one vibration mode (thickness mode) of the transducer is represented in the model, it can only be accurately applied on discs with a thickness much lower than the diameter.

Nominal values of the material properties of the transducer and the structure were supplied by the manufacturers (*Ferroperm Piezoceramics* and *SAAB Aerotech*, respectively), except for the material attenuation in the structure. The attenuation was roughly estimated by measuring the Q-value of the resonance peak with the transducer coupled to the structure using a network analyzer. The attenuation in the model was then adjusted to fit the Q-value in the simulated spectrum to the measured Q-value.

3.1 FEA model

To verify the validity of the one-dimensional approximation and to examine the influence of all vibrational modes of the transducer and the structure a FEA model was implemented. The model was created and solved using the Comsol Multiphysics [1] modeling package. The modeled setup can be considered as axi-symmetric, which greatly reduces the required computation time of the FEA. The geometry of the model is shown in Fig. 4. Three different physical models were used: a piezoelectric for the Pz27 element, an acoustic for the water layer, and an elastic for the Al-adhesive structure. To cancel all reflections in the transversal direction the structure was considered as semi-infinite through the use of a perfectly matched layer (PML, shaded in figure).

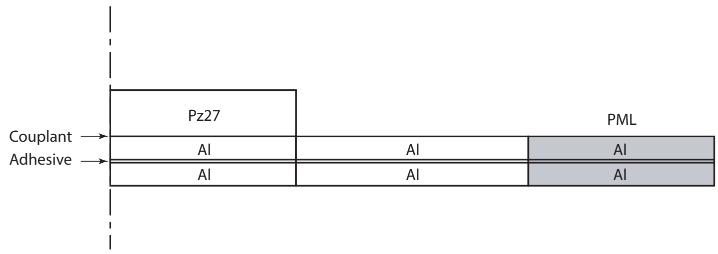

Fig. 4. Geometry of FEA model

3.2 Interface model

As already mentioned, our primary aim is to explore the behavior of different transducers when changes occur in the interface between the adherent and the adhesive rather than to create an exact model of an actual defect. Various types of imperfect bonds have been proposed in the literature along with appropriate models describing different boundary conditions (e.g. [6]). In this paper an interface layer model proposed by Jiao and Rose [7] is used to model the weakened interface between the adherent and the adhesive, resulting in a change of effective elasticity or density. If the material parameters of the interface layer approach the parameters of the adhesive, the bond becomes perfect.

[1] Multiphysics is a trademark of COMSOL, Inc.

The interface layer used here to model the weak bond is 5 μm thick; it has the same properties as the adhesive except a small change of the elastic constant c. It is also assumed that the interface layer is infinite in lateral extent. The interface layer model facilitates transducer selection – it indicates which specific working frequencies and transducers that are most appropriate for detection of small changes in the interface properties.

4 Sensitivity analysis

The relative change in the measured admittance of a transducer, hereby defined as the sensitivity, is substantially affected by the choice of working frequency, which means that some transducers and working frequencies may be practically unusable for certain setups. The sensitivity is defined as the relative impedance change:

$$\eta = \frac{|Y_{nominal} - Y_{defect}|}{|Y_{nominal}|} \tag{11}$$

We will use an illustrative example to enlighten the sensitivity issue. Let us consider a typical NBUS setup shown in Fig. 5. The transducers used in this setup have the form of 20 mm discs of different thickness made of Pz27, a PZT piezoelectric material from *Ferroperm Piezoceramics* [8]. The transducer element is undamped, i.e., it has neither backing nor front layer and is coupled to the structure by a thin layer of water. The inspected object is a simple bonded multi-layer structure used in the aircraft industry, two identical 1.6 mm aluminium plates bonded by a 0.1 mm layer of adhesive. The properties of the imperfect layer is purely hypothetical, such as the magnitude of the elasticity change, and are only used to illustrate the concept. This also applies to the magnitude of the couplant variation. The center frequency of the trans-

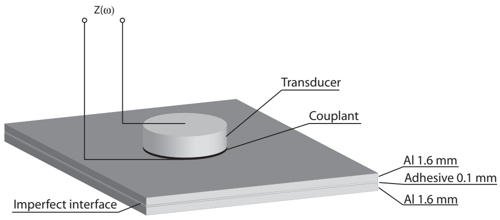

Fig. 5. NBUS Setup used for the inspection of layered structure

ducers used in our simulations ranges from 200 kHz up to 2 MHz, or in terms of PZT thickness from 10 to 1 mm. Since the design of the transducer is the main concern, the simulations are performed using the transducer thickness as varying parameter.

4.1 Transducer sensitivity

To introduce the sensitivity problem let us look at the case presented in Fig. 6, which shows a simulation of the relative admittance change for a 3.6 mm thick Pz27 transducer in the setup shown in Fig. 5 for different elasticities in the interface layer between the adhesive layer and the upper Al-plate (see Section 3.2 for details). From Fig. 6 it can be seen that the transducer's sensitivity to changes in the interface depends on the working frequency, that is: the best choice of working frequency offers several times higher sensitivity than other frequencies. Extending this analysis to a range of transducer dimensions

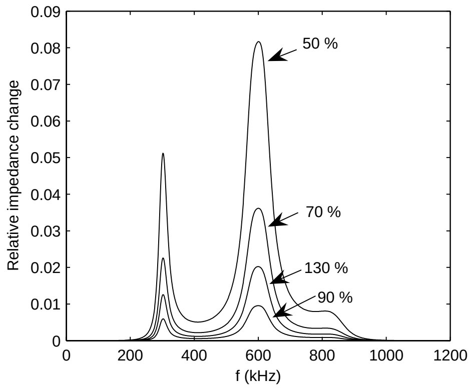

Fig. 6. Relative admittance change of a 3.6 mm Pz27 transducer corresponding to 50%, 70%, 90% and 130% values of the nominal elastic constant in the interface model.

results in Fig. 7, showing the relative admittance change corresponding to a 20% change of the interface elastic constant for a whole range of transducer thicknesses (from 1 mm to 10 mm) and for frequency range from 50 kHz to 1.2 MHz. The two bright lines well pronounced at the left hand side of Fig. 7 represent two fundamental resonances in the system: half-wave resonance occurring at the lowest frequencies, and full-wave resonance. Both resonances can be easily observed in Fig. 6 as two separate maxima in the plot of relative admittance change. Fig. 6 is in fact a section of Fig. 7 along the constant thickness line corresponding to 3.6 mm. The continuous white line in Fig. 7 represents the resonance frequencies of the free oscillating transducer. It is clear that the transducer's fundamental resonance frequency is not the best choice of working frequency for this setup and it is in general far from being the optimal choice. It is apparent that the highest sensitivity can be obtained using the second resonance mode (dashed gray line).

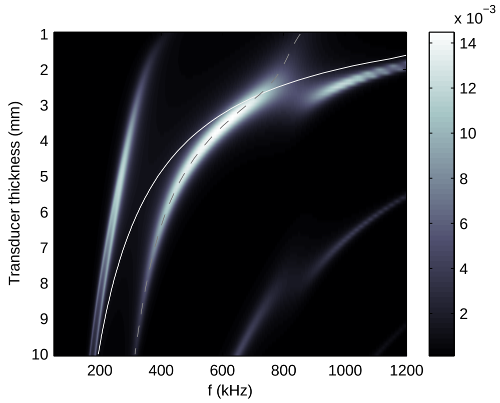

Fig. 7. Relative admittance change due to 20% change of the nominal elastic constant in the interface model. White solid line indicates resonance frequency of the free oscillating transducer in air and dashed gray line the second resonance mode of the coupled system.

4.2 Couplant thickness

Sensitivity to variations in coupling between the transducer and inspected material is an important issue that has to be taken into account when choosing NBUS transducers and their working frequency. Sensitivity to couplant thickness can limit the practical applicability of NBUS inspection. Maximizing sensitivity to certain defects should be performed taking into account the robustness of the NBUS test, that is, insensitivity to couplant thickness variations.

The sensitivity issue is illustrated in Fig. 8 showing the relative admittance change due to a small change in the water couplant thickness. Two other examples also illustrating this issue are shown in Fig. 9 where the sensitivity of the 3.6 mm thick transducer can be compared to that of a 2.5 mm thick transducer. It is clear that the 2.5 mm transducer is much more sensitive to changes in the coupling layer around its optimal working frequency than the 3.6 mm transducer (the resonance frequencies in air are 560 kHz and 700 kHz respectively). This trade-off between the sensitivity to defects and the sensitivity to coupling is discussed in detail in the next section.

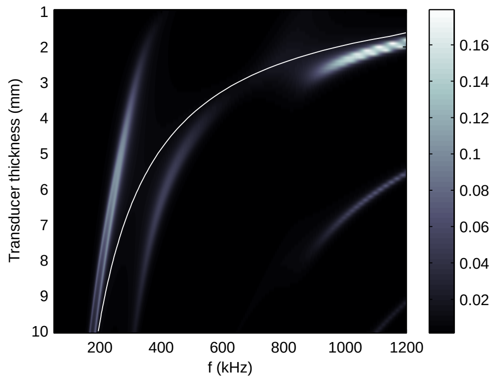

Fig. 8. Relative admittance change of a $+1\mu$m thickness change in the water coupling layer (nominal thickness: 30 μm). White solid line indicates the transducer's resonance frequency.

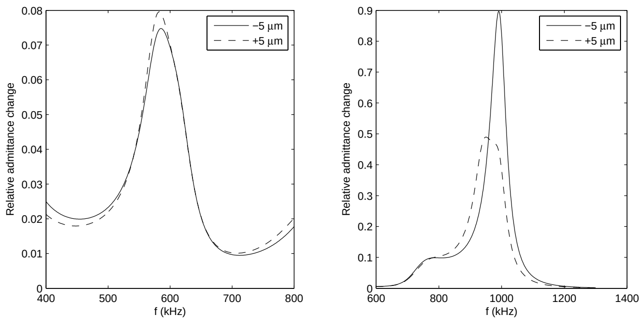

Fig. 9. Relative admittance change of two transducers coupled to the structure for a change in the water coupling layer of $+5\mu m$ and $-5\mu m$ (nominal thickness: 30 μm). A 3.6 mm thick transducer (left) and a 2.5 mm thick transducer (right).

5 Optimal selection of transducer resonance frequency and working frequency

5.1 Standing wave patterns

Below, we present the theoretical explanation of the performance variations of different transducers, which will facilitate interpretation of the examples presented above.

Standing wave patterns of the excited structure of the type shown in Fig.

10 are a powerful tool when analyzing an NBUS setup. The wave patterns calculated for a particular transducer thickness at resonance show where in the structure force or particle velocity nodes and anti-nodes occur. The solid line in Fig. 10 shows the force and the dashed line the particle velocity standing wave pattern of the two lowest resonance modes in the simulation from Fig. 7. The first mode (left) corresponds to the half wave resonance of the system using a 5.5 mm transducer. The second mode (right) is the full wave resonance using a 3.5 mm transducer. Note that in the first mode the maximum force occurs in the coupling layer. In the second mode the maximum force is at the imperfect bond while the local minimum is placed in the coupling layer.

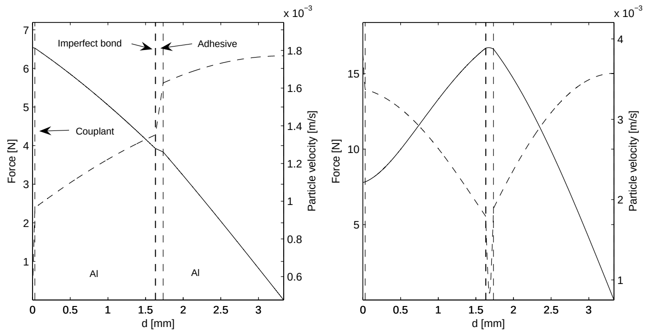

Fig. 10. Standing wave pattern in the structure of the two lowest resonance modes of force (solid) and particle velocity (dashed).

5.2 Guidelines

Analysis of the resonances of the coupled system is the key to successful use of NBUS. The working frequency should be selected in the frequency band corresponding to one of the resonance modes.

The next important factor to consider is a high value of the effective coupling factor k_{eff} (Eq. (10)). The coupling factor of the transducer coupled to the structure depends on both the properties of the transducer and the structure. It also depends on which mode the system is resonating in. Material loss is a limitation for higher working frequencies and thinner transducers. Disregarding loss in the model can easily lead to conclusions such as that higher resonance frequencies result in a higher k_{eff} and thus higher sensitivity, which is in practice limited by loss.

Transducer design is concerned with maximization of the sensitivity to areas of interest and minimization of the sensitivity to coupling conditions. The total mechanical energy density in an elastic material (Eq. (9)) consists of two terms, the kinetic energy density and the elastic energy density. The kinetic energy is determined by the particle velocity v and the density ρ and the elastic energy by the stress T (related to force (F) through Eq. (1)) and the elastic constant c.

Our example can be seen as an idealized case where only the elastic constant is changed. It is reasonable to assume that a real defect affects both elasticity and density. Since the kinetic energy is unaffected by a change of the elastic constant the natural approach is to place the point of maximum force in the standing wave pattern in the layer of interest to maximize the change in energy. Maximum force coincides with minimum particle velocity. This is illustrated in the right plot of Fig. 10.

Assuming that the density is constant in the coupling layer, a thickness change of the coupling medium gives the same effect as a change of the elastic constant. The difference from the case above is that sensitivity is to be minimized. This is achieved by placing the minimum point of force in the standing wave pattern in the coupling layer. This condition is seen in the right hand plot in Fig. 10.

5.3 Discussion

To use the design guidelines formulated above one needs curves similar to those shown in Figures 10 and 11 plotted for the particular test setup. By observing Figures 7 and 8 it is apparent that that the second resonance mode meets the requirements of sensitivity and robustness. The plots in Fig. 11 show respectively, the effective coupling factor k_{eff} and the sensitivity along the second resonance mode when the resonance frequency for each transducer thickness has been selected. The left plot illustrates the sensitivity to changes in the interface and the right plot the sensitivity to changes in the coupling layer. In the left plot the strong correlation between k_{eff} and the sensitivity is apparent. In the right plot there is a large discrepancy for transducers with thicknesses between 2 and 6 mm. This is the case shown in the right plot Fig. 10 when there is a force minima in the coupling layer. Summarizing these observations: the Pz27 transducer used for this example should be approx. 3.6 mm thick (resonance frequency approx. 600 kHz) to maximize the sensitivity to interface defects and to minimize the sensitivity to coupling condition. Fortunately these two objectives are met for the same transducer dimension and working frequency in this particular example. In the general case, however, with structures asymmetric around the defect zone the optimal selection is less obvious.

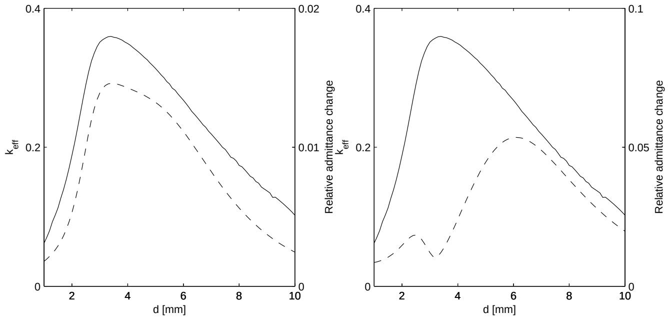

Fig. 11. Illustration of the correlation between coupling efficiency k_{eff} (solid) and sensitivity (dashed). Change in the interface layer (left) and a change in the couplant thickness (right).

Results obtained from the simplified one-dimensional model can be compared with those obtained from a more accurate FEA model in Fig. 12, which shows the FEA simulation corresponding to the simulation results shown in Fig. 7. The two models show good agreement for the second resonance mode, especially close to the optimal working frequency of the optimal transducer. For lower working frequencies and thicker transducer elements the agreement becomes worse. This is due to other modes of vibration present in the transducer, such as radial modes (vertical lines in Fig. 12). Apart from making it difficult to select an appropriate transducer and working frequency, these modes reduce the sensitivity of the transducer through mode coupling. Transducer manufacturers have developed techniques to dramatically weaken the undesired modes and create a transducer with an almost pure resonance mode.

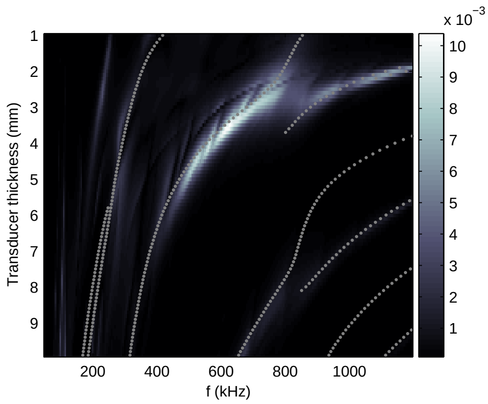

Fig. 12. FEA simulation corresponding to Fig. 7. Dotted lines indicate peaks obtained from the one-dimensional simulation.

6 Conclusions

The performance of NBUS inspections can be greatly improved by using simulations that facilitate understanding of how different transducers behave at different working frequencies. By creating a model of the setup, the sensitivity to defects and robustness toward changes in the coupling can be optimized either by designing an application specific transducer, or by efficiently using the available equipment through the selection of a proper working frequency. The interface layer model has been used to compare the performance of different transducers and working frequencies on an imperfect bond. The parameters of the interface layer should represent the effective elasticity and density of the interface. The effective parameters of the imperfect bond are in practice difficult to estimate, which is the reason for using hypothetical values.

We have shown that analyzing standing wave patterns can be very valuable during the transducer design. The inspected structure used as an example in this work proved to be very advantageous since a very good trade-off between the sensitivity to bond defects and the optimal robustness toward changes in the coupling layer could be found.

It is worth noting that minimum sensitivity to the coupling condition always occurs at the same frequency as the structure's fundamental resonance frequency. The reason is that a minima in the force standing wave pattern will occur at both sides of the structure, providing minimum force in the coupling layer.

The lateral extent of the defect determines the expected detectability. It is reasonable to assume that transducer elements with larger diameter have greater penetration depths, while they are also less sensitive to defects of limited lateral extent, that is, defects smaller than the transducer area. This issue, however, should not affect the optimal thickness of the transducer element.

Acknowledgment

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Paper II

Presented at the 2005 IEEE Ultrasonic Symposium in Rotterdam, Holland.

Designing and Evaluating Transducers for Narrowband Ultrasonic Spectroscopy

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Abstract— **Introduction of new composite materials in aerospace applications has created a demand for an efficient NDE technique. Ultrasound resonance inspection is especially suitable for the inspection of multilayered structures. In the narrowband ultrasonic spectroscopy (NBUS), which has been developed recently [1], the surface of an inspected structure is scanned with a resonant transducer whose frequency response is monitored in a narrow frequency band. The paper is concerned with optimizing the NBUS setup consisting of a piezoelectric transducer coupled to a multi-layered structure. Differences in the electrical impedance of a piezoelectric transducer caused by variations of parameters of the inspected structure are estimated using an equivalent circuit model and a finite element tool. Design guidelines for NBUS transducers are presented, including an explanation for why NBUS transducers can efficiently operate at lower frequencies than those adequate for pulse-echo ultrasonics od similar objects.**

I. Introduction

In a broadband ultrasonic resonance spectroscopy (URS) test a frequency spectrum of the inspected object is acquired and an analysis is performed to evaluate material properties and/or to detect flaws. A broadband transducer, weakly coupled to the inspected structure acquires its frequency response in some frequency band where a number of resonances should occur. The resonance frequencies depend on a number of factors, such as, material composition, temperature and the presence of flaws in the structure. A transmitting transducer is excited by a swept frequency signal and the spectrum is acquired using a number of receiving transducers. Changes in the condition of the structure will influence the position of the resonances in the frequency response and a diagnosis can be performed using some pattern recognition method.

Narrowband ultrasonic spectroscopy (NBUS) uses a slightly different approach to URS. NBUS operates on the principle of monitoring the electrical impedance at a certain frequency, the working frequency, of a piezoelectric probe coupled to the inspected multilayered structure. Since a piezoelectric transducer is an electromechanical device the parameters of its electrical resonance depend on its mechanical load, i.e., the acoustic impedance of the inspected material. Thus, in this kind of test, the resonance spectrum of the inspected structure is not measured directly but through its influence on the resonance spectrum of a narrowband transducer. A feasible way of extracting information about the inspected structure using a narrowband piezoelectric transducer is sensing variations of its electrical impedance caused by the varying conditions of the inspected structure. The electrical impedance for a predefined frequency in the vicinity of transducer's resonance is relatively easy to measure using a vector voltmeter.

Changes in the multilayered structure, e.g. disbonds or imperfections in the interface between the adherent and the adhesive (kissing bond) will change the acoustic impedance at the front side of the probe coupled to the structure. This will result in a change of its spectrum, which will be pronounced at certain frequency bands depending on the transducer, the structure, and the type of flaw. Selecting an appropriate transducer and an appropriate working frequency are the two most important choices when using NBUS.

It has been proven that the NBUS method is capable of detecting both artificial delaminations in multilayered aluminium structures as well as artificial delaminations and impact defects in carbon fiber composites [1]. A few instruments utilizing this principle is already commercially available, e.g. the BondMaster from Staveley NDT Technologies.

In practical use of the technique, the working frequency is selected ad hoc, based on the manufacturer's recommendations and user experience. The probe's resonance frequency in air is not necessarily a bad choice, but the resonance frequencies of resonant narrowband probes coupled to a structure are shifted, making room for better selections.

We have explained the NBS principle and presented some of its applications in our previous publications, [1], [2]. Here, we use simulation results to explain some interesting features of this method and to formulate guidelines for designing the NBUS transducers. We use the KLM equivalent circuit model which takes into account mechanical loads on both surfaces of a piezoelectric element to model the NBUS setup and we verify the obtained results using a finite element model (FEM). We examine an imperfect bond between an aluminium plate and an adhesive layer and its effect on different transducers.

One of the major problems with NBUS is its sensitivity to coupling. We address this issue and show how to decrease the influence of coupling maintaining a high sensitivity to defects.

II. Narrowband Ultrasonic Spectroscopy

A. Setup

A typical NBUS setup, which is also used in this work is shown in Fig. 1. The transducers considered below have the form of 20 mm discs of different thickness made of PZ27 piezoelectric material PZT from Ferroperm [3]. The transducer

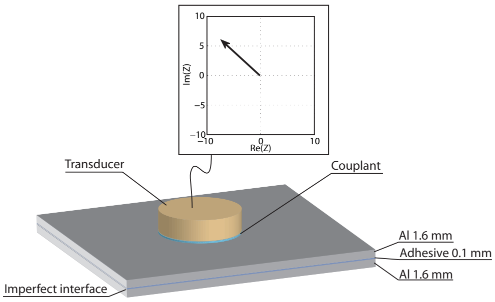

Fig. 1. NBUS Setup used for the inspection of double layered structure

element is undamped, i.e., it has neither backing nor front layer and is coupled to the structure by a thin layer of water. The object considered here is the simplest bonded multi-layer structure, two identical 1.6 mm aluminium plates bonded by a 0.1 mm layer of adhesive.

The transducer impedance variations measured at a selected working frequency is influenced by the state of the inspected structure and/or the acoustic coupling. Narrowband transducers are preferred for NBUS measurements due to their superior sensitivity, provided the correct working frequency is chosen.

The center frequency of the transducers used in our simulations ranges from 100 kHz to 2 MHz. Since the design of the transducer is the main concern, the simulations are performed with the transducer thickness as the varying parameter. The reason for this is that the resonance frequency is not governed solely by the thickness of the element, which makes it impractical as a reference.

B. Modeling

The issue here is not to create a perfect model of the physical setup, but rather to present an approach that can be used when designing NBUS transducers, and to determine at which working frequencies the detection of specific defects is most likely. This approach enables designing application specific transducers for the applications where standard transducers used in pulse-echo mode yield poor results, for example, for the detection of imperfect bonds.

Two different models have been used in this work: the equivalent circuit KLM model [4] for most of the results presented, and an axi-symmetric FEM to verify the conclusions drawn from the KLM modeling.

The KLM model has the form of an electromechanical three-port network with an electrical input connected through a transformer to an acoustic transmission line with two inputs: the front and back of the transducer. Since only one vibration mode (thickness mode) of the transducer is represented in the model, only discs with a thickness much lower than the diameter can be considered.

To calculate acoustic impedance at the acoustic inputs of the KLM model the multilayered structure is modeled using Brekhovskikh's transmission line model [5].

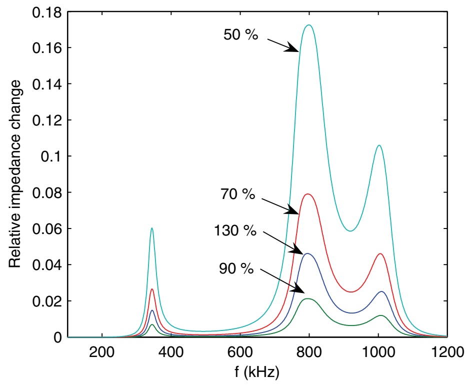

Fig. 2. Impedance change of a 780 kHz Pz27 transducer corresponding to the 50%, 70%, 90% and 130% values of the nominal Young's modulus in upper Al-adhesive interface layer.

The FEM was created and solved using the Comsol Multiphysics[1] modeling package. Three different physical models were used: the piezoelectric for the Pz27 element, the acoustic for the water layer, and the structural mechanics for the Al-adhesive structure. To cancel all reflections in the transversal direction the structure was considered as semi-infinite by the use of a perfectly matched layer.

Nominal values of the material properties of the transducer and the structure were supplied by the manufacturers (Ferroperm and SAAB, respectively), except the material attenuation in the structure, which was tuned manually.

C. Interface model

As already mentioned, our primary aim is to explore the behavior of different transducers when changes occur in the interface between the adherent and the adhesive rather than to create an exact model of an actual defect. Various models of imperfect bonding have been proposed in literature along with appropriate models describing different boundary conditions (e.g. [6]). In this paper an interface layer model proposed by Jiao and Rose [7] was used to model the weakened interface between the adherent and the adhesive. The interface layer used here for modeling the weak bond is 5 μm thick; it has the same properties as the adhesive except a small change of the Young's modulus. The interface layer model facilitates transducer choice – it indicates which specific working frequencies are the most appropriate for detecting small changes in the interface properties.

III. Sensitivity to Weakened Bonds

The relative impedance shift due to changes in the inspected structure is highly dependent on the transducer and the working frequency. As an example, Fig. 2 shows a simulation of the

[1]Multiphysics is the trade mark of COMSOL, Inc.

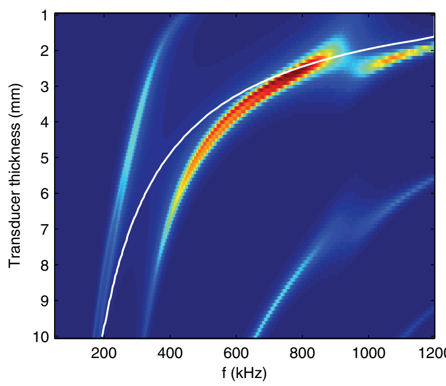

Fig. 3. Relative impedance change due to 20% change of the nominal Young's modulus. White line indicates transducer's resonance frequency.

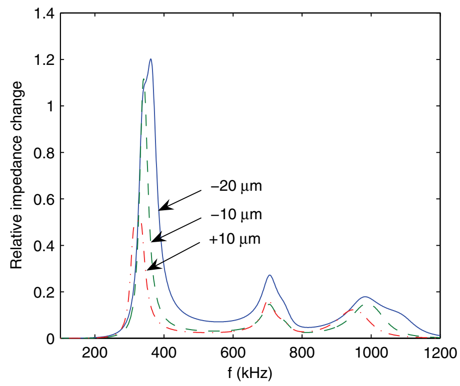

Fig. 4. Relative impedance changes of the 670 kHz transducer for -20μm, -10μm and +10μm change in the coupling layer (nominal: 30 μm)

relative impedance change for a 780 kHz Pz27 transducer for different elasticities in the interface layer between the adhesive layer and the upper Al-plate. The first maximum at approx. 350 kHz corresponds to the lowest thickness resonance of the coupled system (transducer plus structure) while the second maximum is due to the transducer's own resonance. From Fig. 2 it can be seen that the transducer's sensitivity to the changes in the interface depends on the working frequency, that is, the correct choice of the working frequency offers several times higher sensitivity than other frequencies. Since the adhesive layer is much thinner than the wavelength, the optimal frequency is valid for both the top and bottom Al-adhesive interface.

A complete simulation showing the relative impedance change corresponding to the 20% change of Young's modulus in a whole range of transducer dimensions (from 1 mm to 10 mm) and for frequencies between 50 kHz and 1.2 MHz is shown in Fig. 3. The white line represents the resonance frequency of the free oscillating transducers. It is clear that the transducer's resonance frequency is rarely the best choice of working frequency.

IV. Sensitivity to couplant thickness

Sensitivity to variations in coupling between the transducer and inspected material is an important issue that has to be taken into account when choosing NBUS transducer and working frequency. Sensitivity to the couplant thickness can limit the practical applicability of the NBUS inspection. Maximizing sensitivity to certain defects should be performed taking into account robustness of the NBUS test, that is, insensitivity to couplant thickness variations.

This is illustrated in Fig. 4 showing the relative impedance change due to changes in couplant thickness as a function of frequency for the 780 kHz transducer (the same as in the previous section) and assuming the nominal couplant thickness is 30 μm.

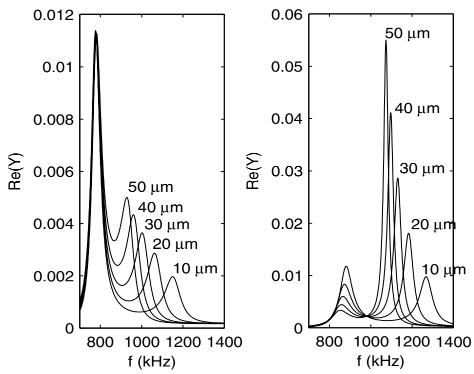

Fig. 5. Admittance of two transducers coupled to the Al-adhesive structure for five different couplant thicknesses, the 780 kHz transducer (left) and a 1.0 MHz transducer (right).

Two examples also illustrating this issue are shown in Fig. 5 where the sensitivity of the 780 kHz transducer (left) can be compared to that of a 1.0 MHz transducer (right). It is clear that the 1.0 MHz transducer is much more sensitive to changes in the coupling layer around its fundamental resonance frequency than the 780 kHz transducer. This trade-off between the sensitivity to defects and the sensitivity to coupling is discussed in the next section.

V. Optimal selection of transducer resonance frequency and working frequency

For the 780 kHz transducer used in the previous examples the selection of working frequency is simple. Fig. 6 (top) illustrates both the relative impedance change for a 20 % change of the Young's modulus in the upper interface and the impedance change for a 1 μm change of the couplant

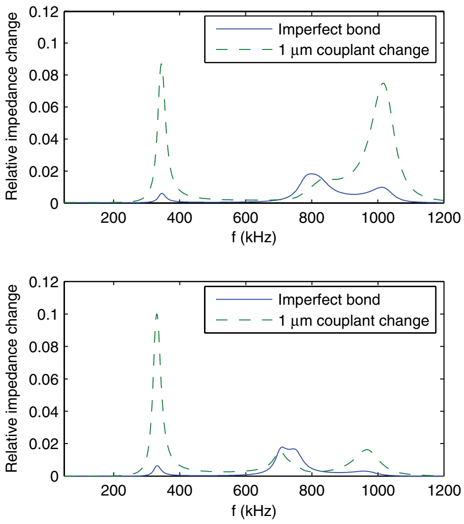

Fig. 6. Comparison between impedance change on 20% change of the Young's modulus in the upper Al-adhesive interface and 1μm change in couplant layer for a 780 kHz (top) and a 670 kHz (bottom) Pz27 transducer.

thickness. The best choice of working frequency is obviously around 780 kHz which offers the highest ratio between defect sensitivity and couplant thickness sensitivity. This is not as obvious for the 670 kHz transducer shown in Fig. 6 (bottom). The highest sensitivity toward bond interface changes occurs at 710 kHz, but this is also a local peak for the couplant thickness sensitivity. The best ratio is achieved around 770 kHz, i.e. the same frequency as for the 780 kHz transducer. In fact 770 kHz is always the best selection for any transducer in terms of ratio on this particular structure. The reason for this is that 770 kHz corresponds to the lowest thickness resonance frequency of the Al-adhesive structure. However, looking solely at the ratio can be very dangerous because the high ratio can be caused by a minima in the couplant thickness sensitivity in the frequency band where the transducer has an immeasurably small defect sensitivity. Summarizing, transducer modeling offers a solution to the trade-off between the sensitivity to defects and the sensitivity to changes in the coupling which is the most important compromise when designing an application specific NBUS transducer.

VI. Conclusions and Future Work

The performance of NBUS inspections can be greatly improved by using simulations that facilitate understanding of how different transducers behave at different working frequencies. By creating a model of the setup, the sensitivity to defects and robustness towards changes in the coupling can be optimized either by designing an application specific transducer, or by efficiently using the available equipment through the selection of a correct working frequency.

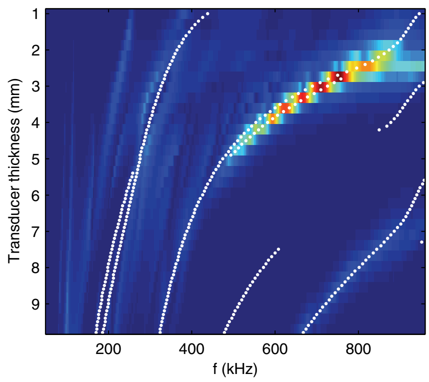

Fig. 7. FEM simulation corresponding to Fig. 3. White line indicates peaks from the KLM simulation.

Fig. 7 shows the result of the FEM simulation of the relative impedance change due to a 10% change of the nominal Young's modulus for different transducer thicknesses. White line indicates the positions of the peaks obtained from the corresponding KLM simulation. The comparison shows a good agreement between the two models. This facilitates efficient optimization of the transducer geometry and working frequency. Although simulation using the one-dimensional KLM model seems accurate enough for the application it may be insufficient in some situations. Further investigation is carried out to establish when the use of the FEM simulation might be required.

Acknowledgment

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Paper III

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Narrowband ultrasonic spectroscopy for NDE of layered structures

T Stepinski and M Jonsson

NDE of airspace sandwich structures is often performed using a simple resonant transducer sensing the information in the frequency domain obtained due to the constructive and destructive interference of elastic waves. Application field of ultrasonic narrowband ultrasonic spectroscopy (NBS) is likely to increase rapidly with the growing application of layered structures in modern aircraft, for example, GLARE. The aim of this paper is to enlighten the potential and the limitations of the NBS techniques. Operation of the NBS technique based on the measurements performed using a specially designed resonance transducer with carefully selected narrow frequency band is explained in detail.

A novel method, based on the use of impedance plane for sensing transducer resonance, is presented. Theoretical results illustrate the relation of the impedance plane indications to the adhesive strengths in aluminium sandwich structures. Finally, practical application of the proposed technique on mechanised inspection of carbon fibre reinforced structures is presented.

Introduction

Ultrasonic resonance spectroscopy (URS) utilises information in the frequency domain obtained due to the constructive and destructive interference of elastic waves for non-destructive evaluation of inspected objects. In a resonance test an ultrasonic tone-burst with sweeping frequency is applied to an ultrasonic transducer and a resonance spectrum of the inspected structure is acquired[1]. The acquired spectrum contains primarily information about material properties but it also may say something about the presence of flaws in the inspected structure. Generally, there are two types of resonance test, global and local. The global test provides synthetic information about the entire inspected part and, therefore, it can be applied to relatively small parts where vibrations can be excited in the whole inspected volume. The local test is more suitable for large structures, for instance in aerospace applications, where local structure condition is of interest, and only a selected part of the structure is to be excited.

Ultrasonic resonance spectroscopy has been used for the inspection of aerospace structures and its application field is expected to increase rapidly with the growing application of layered structures in modern aircraft (for example carbon fibre reinforced panels (CFRP) or GLARE)[3]. Despite that commercially available instruments dedicated to this type of inspection have been developed and used for several years (for instance, the Fokker Bond Tester or BondMaster™ from Staveley NDT Technologies), a very limited information concerning the operation principles of the commercially available instruments has been published, except some patent descriptions,[4], [5]. Since new applications compel increased demands on the URS instruments and transducers in terms of their sensitivity and their ability to characterise defects it is of value to the NDT community to get better understanding of the techniques that are in use.

A fundamental limitation of resonance inspection is its sensitivity to factors that are unessential for the test, such as variations in dimensions or material properties that may mask the effect of smaller defects. This problem can be solved either by modelling or, when modelling is unfeasible, by employing sophisticated self-learning algorithms for tuning parameters of the flaw detector. In the case of multilayered aerospace structures, modelling seems to be the most suitable solution.

The purpose of the present paper is to enlighten the potential and the limitations of the URS techniques. The presented material is a result of our research aimed at the development of narrowband ultrasonic spectroscopy (NBS) capable of coping with new applications and the increased demands. We start from explaining NBS principles for multi-layered structures and presenting a model enabling modelling the tested structure and the transducer. Then, we show an efficient solution to the sensor problem based on measuring its electrical impedance and, finally, we present some results of mechanised NBS inspection.

Measurement set-up

The URS instruments (bond testers) that are used mainly for the inspection of aircraft structures operate on the principle of exciting a thickness resonance in a multi-layered structure. A piezoelectric probe, excited by a swept frequency signal, is coupled to the surface of the inspected structure using a coupling agent (see Figure 1). The instrument acquires probe's frequency spectrum in the frequency range from some tens of kHz to several hundreds of kHz. A thickness resonance in the layered structure occurs when the echoes reflected due to the difference in acoustic impedances at the boundaries, travel back and forth between the two boundaries creating a standing wave. For multi-layered structures, a number of resonance modes can be observed depending on the structure's geometry and condition. A characteristic resonance pattern, an ultrasonic signature, obtained for each particular defect-free structure and given transducer can be used as a reference when assessing the structure's condition.

Since a piezoelectric transducer is an electromechanical device, its electrical impedance depends on mechanical load, *ie*, the acoustical impedance of the inspected material. This is illustrated by Figure 1, where the KLM equivalent circuit is used to illustrate transducer operation (for details concerning the KLM model see[6]). The inspected structure that acts as a mechanical load for the transducer results in a change of its resonance characteristics. Generally, resonance frequency of a loaded transducer will be shifted and its resonance peak will be widened.

In the narrowband resonance inspection of a structure, its surface is scanned with a resonant transducer and the transducer frequency response is monitored in a narrowband. Disbond detection is performed by an operator observing simple features of the acquired spectra, such as a shift in the resonance frequency or a

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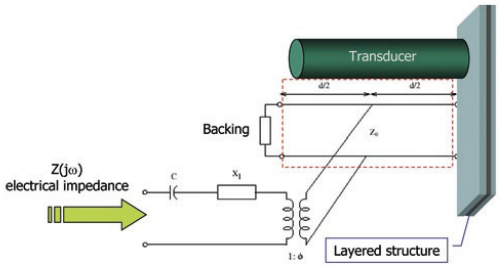


Figure 1. Principle of the narrowband ultrasonic spectroscopy test of a layered structure and the KLM model of the piezoelectric transducer used for the test

phasor corresponding to the transducer's electrical impedance for a pre-selected frequency in the vicinity of its resonance.

The resonance frequency monitoring is applied in Bond Tester from Fokker[5]. However, serious difficulties may be encountered when applying the frequency shift based NBS to attenuating materials, for instance CFRP. Resonance of a probe coupled to such

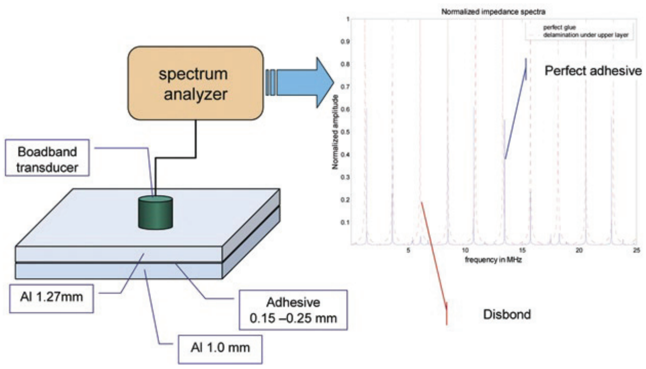


Figure 2. Al structure with two layers and its simulated acoustic impedance seen by the transducer coupled to the top layer

structure is not only shifted in frequency but also spoiled in the sense that the resonance peak broadens so much that the accurate detection of the resonance frequency may be difficult. It is worth mentioning that probe characteristics are crucial for the NBS test, since the shift of its resonance frequency indicates condition of the inspected structure. Therefore, highly resonant piezoelectric probes are preferred for this kind of test.

The abovementioned difficulty can be eliminated by using the second technique, *ie*, the measurement of transducer's electrical impedance. Probably the first instrument designed according to this patented principle was BondaScope 2100 from NDT Systems, Inc. USA (see[4] for details); later another instruments, such as, BondMaster™ from Staveley NDT Technologies and Bond Tester from Zetec have been released. As illustrated by the equivalent circuit in Figure 1, the transducer transforms variations of the mechanical load of the transmission line at the mechanical side to the electrical impedance at the primary side. Thus, a change in acoustical impedance of the inspected structure will be reflected as the respective change of the transducer's electrical impedance.

In both solutions that were presented above, the operator has to perform a simple spectrum classification task based on the primal features extracted by the instrument. Below, we present models that explain in more detail the impedance monitoring principle, which seems to dominate in the market today.

Structure modelling

A software toolbox has been developed for calculating the acoustical impedance of sandwich structures consisting of a number of semi-infinite parallel layers. Material constants, such as density and sound velocity, are used as parameters. The software, which is written in Matlab™, applies a model based on the transmission line concept for recursive calculation of the impedance seen from the top of the successive layers. It is assumed that a longitudinal plane wave is incident on the structure's top boundary; details can be found in[2, 8-10]. Material attenuation is not included in the model.

Assuming that acoustical impedances and thicknesses of the individual layers are known, the model implemented in the toolbox calculates the impedance of the multi-layered structure. The software has been used for simulating laminated airspace structures consisting of aluminium layers bonded by adhesive layers. Spectral variations due to the disbonds and voids between the aluminium plate and the adhesive can be modelled and evaluated. As an example, Figure 2 shows the results obtained for a simple laminated structure consisting of two aluminium plates

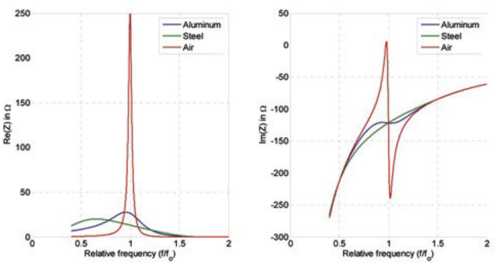


Figure 3. Impedance of the transducer shown in Figure 3 in the air (red), after loading it with aluminium (blue) and steel (green)

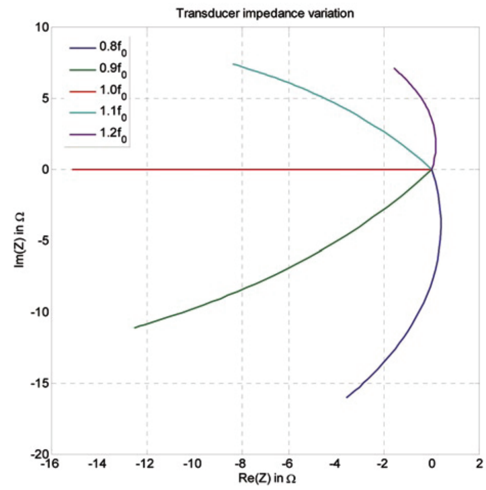


Figure 4. Theoretical transducer impedance variation for load impedance variation from Al (origin) to steel for five different frequencies close to transducer resonance

(top 1.27 mm and bottom 1.0 mm) bonded with 0.2 mm adhesive, respectively, for the sound adhesive and a complete disbond. From Figure 2 it can be seen that, when a disbond is present, the layered structure becomes a single plate characterised by a very regular spectrum.

Disbonds would be relatively easy to detect if the variations in the spectra measured for a defect-free structure (nominal spectra) were small. Unfortunately, variations of the adhesive parameters (mainly its thickness) may result in quite large shifts of the resonance peaks and also variation of their amplitude. Another difficulty can arise when the disbond is not complete (so called *kissing bond*) or it is filled with the aircraft fuel.

Transducer modelling

A narrowband, piezoelectric low frequency transducer (below 1 MHz) is a vital part of the NBS set-up. Since the transducer is undamped, it has a distinct frequency peak corresponding to its thickness mode (*cf.* [2], [6]).

Piezoelectric transducers are electromechanical systems that can be modelled in many ways depending on the application. Here, the KLM model[6], based on the transmission line concept, was chosen since it enables modelling the transducer under various load conditions. In the KLM model the acoustical side (a transmission line of a length d corresponding to the thickness of piezoelectric element) is coupled to the electrical side by a transformer with ratio ($1{:}\phi$) (see Figure 1). The transmission line has two ports where acoustical loads are applied, backing at the left-hand side and the inspected structure at the right-hand side. Thus, the influence of the load variations on the transducer's electrical impedance can be modelled.

In other words, when a piezoelectric transducer is used for inspecting a multi-layered structure, as shown in Figure 1, the structure's acoustical impedance can be directly plugged into the KLM model and the electrical impedance of the transducer calculated using this model will reflect variations in the inspected structure. Before this can be done, parameters of the transducer model have to be estimated using an adequate procedure.

An example of modelling is presented in Figure 3 where the impedance plot of a 1 MHz transducer in air can be compared with that of the transducer coupled to aluminium and steel, respectively. It should be noted that the impedance plots were simulated using the KLM model for an idealised 1 MHz transducer made of PZT27 and neither backing nor wear plate of the transducer were included in the model. For a real transducer the impedance in the air would be much closer to that of the loaded transducer.

Figure 4 illustrates problems encountered when using resonance frequency shift as a significant feature for the inspection (for instance in Fokker Bond Tester), the resonance of a loaded transducer is, in general, difficult to detect, especially, in practical situations where the impedance plot may be far from smooth. An attempt was made to use an automatic detector circuit employing a phase locked loop (PLL) circuit for tracking resonance frequency of a piezoelectric resonator. The automatic detector was tested on triple-layered Al structures with artificial disbonds, the results can be found in [9] and [10]. The measurements and the simulations have shown a significant difference between the resonance frequencies corresponding to lower and upper disbonds in Al structures. However, sensitivity of this method was sufficient neither for the evaluation of kissing bonds produced in Al samples nor for detecting defects in CFRP. Poor results obtained in the demanding applications motivated the development of the method based on sensing transducer's impedance for a single, carefully selected frequency.

Contrary to resonance frequency, the electrical impedance can be reliably measured for any frequency and, since it is a complex valued variable, it yields two parameters that can be used in the similar manner as in the eddy current technique. This is illustrated by Figure 4 showing the theoretical (modelled) transducer impedance variation for the load impedance continuously changing from that of aluminium to steel, respectively. It is apparent that, for different frequencies in the vicinity of transducer resonance, different phase angles and amplitudes are obtained for the same variation of load impedance; for the resonance frequency the respective change is pure real, while for other frequencies the imaginary part is also observed.

Variations of the transducer impedance

Transducer impedance is a complex valued function of frequency that can be represented as a phasor in a complex plane. Modelling results have shown that transducer impedance measured for some frequency close to its resonance underlies considerable variations depending on the condition of the inspected material.

When the inspected surface is scanned using a piezoelectric probe coupled to the inspected structure, the impedance vector in the impedance plane moves providing additional information, like in eddy current inspection.

To illustrate this we modelled a Fokker probe (a PZT cylinder with diameter approx. 13 mm and thickness 25 mm) coupled to the 3-layered wing skin structure shown in Figure 5. The impedance diagram for this probe is presented in Figure 6 in function of adhesive mass density ρ for test frequencies in the interval from 165 to 200 kHz. From Figure 6 can be seen that frequency change moves the operating point along an arc while the increase of mass density moves it towards the coordinate origin.

In summary, our modelling tool enables the systematic investigation of how different structure parameters (such as, disbonds, adhesive thickness) effect transducer impedance and in this way enables an optimal choice of a suitable probe and its test frequency with respect to the inspected structure. Below, some experimental results obtained from the NBS inspection of the Al multilayered structure wing skin and a CFRP specimen are presented.

Inspection of the Al multilayered structure

A sample of the structure wing skin with the structure shown in Figure 5 was inspected using a set-up consisting of a transducer operating at frequencies in the range of 1 MHz mounted in the XY-scanner and the computerised impedance measuring instrument. The transducer with a diameter of 0.5" was fed with a single frequency sinewave with amplitude approx. 10 $V_{p\text{-}p}$ and its complex impedance measured in the discrete XY-points was stored in a PC. A small volume of water applied on the inspected surface was used to obtain contact between the transducer and the inspected structure. A complex valued C-scan obtained in this way was displayed directly at the PC's screen. The sample had a number of implanted disbonds in both adhesive layers (for details see Figure 7(a)). A small area indicated at Figure 7(a) was scanned and the resulting C-scan is shown in Figure 7(b). From Figure 7(b) can be seen that both disbonds were not only reliably detected but also classified respectively as upper and lower.

Inspection of CFRP specimens

Mechanised inspection of CFRP samples was performed using the set-up described above using a small volume of water as coupling agent.

The step-wise specimen NNC-LP-02 from Tecnitest, Madrid, with variable step thicknesses (1, 3 and 5 mm) was inspected. In each step, six artificial defects were manufactured to simulate delaminations, see Figure 8. The defects manufactured at each step have two sizes, 6 x 6 mm (left column) and 4 x 4 mm (right column in Figure 8). The defects in each column are located at different

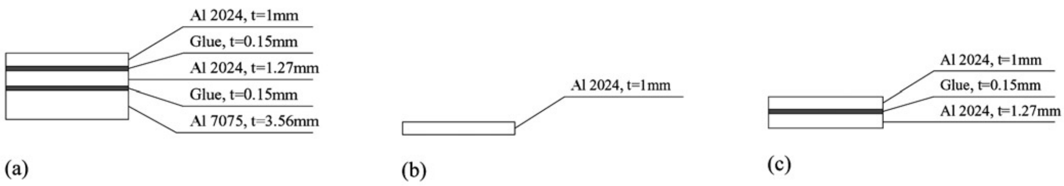


Figure 5. Cross-sections of the wing skin. Sound structure (a), model of the upper disbond (b), and model of the lower disbond (c)

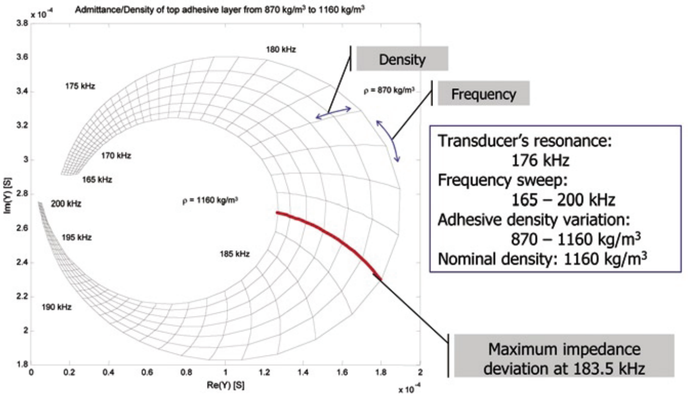


Figure 6. Variation of transducer impedance as a function of adhesive density ρ and frequency *f*

accounting for the effects of natural variations in dimensions and material properties as well as optimising sensitivity of the NBS transducer to disbonds and delaminations. The simulation results obtained using the presented model facilitate understanding the principle of narrowband inspection of multilayered structures.

The preliminary mechanised tests performed using selected specimens yielded very promising results; the proposed method was capable of detecting artificial disbonds in aluminium multilayered structures of different thickness as well as artificial delaminations and natural impact defects in CFRP.

It is worth noting that the impedance NBS can also be performed using broadband transducers capable of sensing a number of structure resonances. Naturally, the sensitivity obtained for the broadband transducer is much

depths: in the lower row in Figure 8 are the defects located at the depth of two plies from the upper surface; in the upper low are the defects located at two plies from the lower surface; and the middle row represents defects in the middle of step thickness.

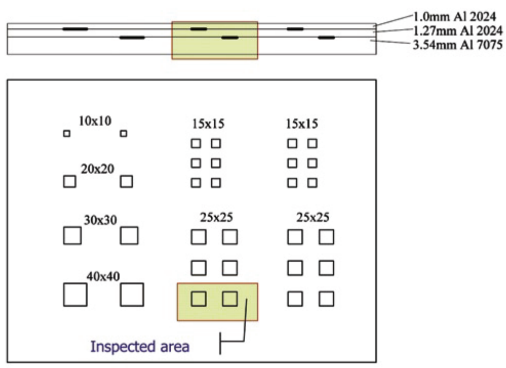
The results are shown in Figure 9 and the ultrasonic C-scan obtained in transmission is appended as a reference. It is evident that the proposed method is capable of detecting almost all defects in the inspected specimen; the most difficult seems to be detecting shallow defects in the thick section of 5 mm. It should be noted, however, that the presented results are preliminary and that the probe used in the experiments has not been optimised for this purpose. Nor have any attempts yet been made to improve the SNR by averaging or other signal processing methods.

Specimens with natural impacts were also successfully inspected in the same set-up, for details see the literature[11].

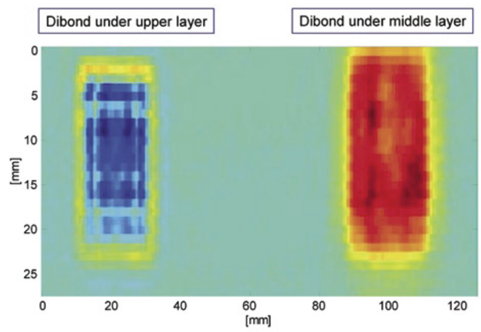
Summary and conclusions

Feasibility of different URS set-ups in application to aerospace layered structures has been investigated and the narrowband spectroscopy (NBS) technique has been selected as the most promising candidate. The method, based on tracing the resonance frequency of a resonant transducer using a PLL circuit, has been developed and examined. It appeared that its sensitivity in more demanding applications was unsatisfactory. An alternative method, based on the sensing probe's electrical impedance, was developed and verified using the Al multilayered structures and the CFRP specimens with artificial and natural defects.

NBS tests of layered structures performed using a narrowband transducer require proper choice of the transducer and its resonance frequency. Today, this choice is performed *ad hoc*, based on the operator's experience and some recommendations from the instrument manufacturer. The tool for modelling the multi-layered structure including the piezoelectric transducer presented in the paper makes this choice much easier and enables maximisation of the transducer indication with respect to the coupling and the parameters of the inspected structure. The model enables



(a)



(b)

Figure 7. Results of NBS inspection of the specimen wing skin with artificial disbonds. Specimen structure (a) and the NBS scan of the indicated area with two disbonds (b)

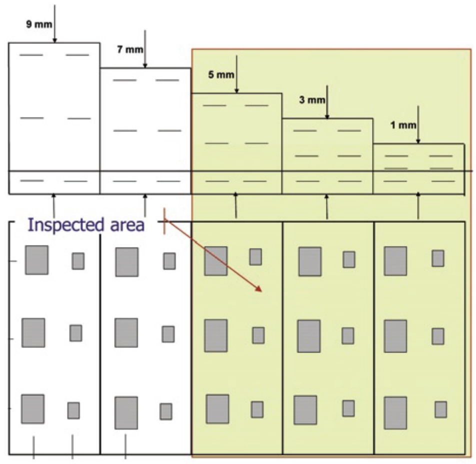


Figure 8. Structure of the step-wise specimen NNC-LP-02 with artificial delaminations

lower than that for a weakly damped one. Interestingly, even transducers with a resonance frequency considerably lower than that of the structure's fundamental modes can be successfully used for the NBS.

Acknowledgments

This work was supported by two projects funded by the European Community: INCA (Contract No: G4RD-CT2001-00507) and NANOSCAN (Contract No: G4ST-CT2002-50288). An instrument has been developed from this work, and is now available from NDT Consultants Ltd in the United Kingdom for testing composites.

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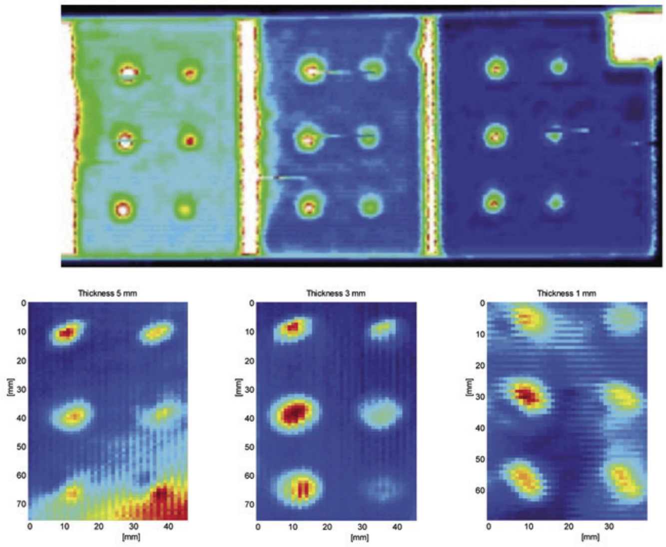

Figure 9. Inspection results obtained for the step-wise specimen of CFRP. Ordinary ultrasonic C-scan obtained in through transmission (upper panel) and C-scans obtained using the proposed method (lower panels)

Paper IV

Presented at the *16th World Congress on NDT*, 30th August - 3rd September 2004, Montreal, Canada.

NARROWBAND ULTRASONIC SPECTROSCOPY FOR NDE OF LAYERED STRUCTURES

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Abstract: NDE of airspace sandwich structures is often performed using a simple resonant transducer sensing the information in the frequency domain obtained due to the constructive and destructive interference of elastic waves. Application field of ultrasonic narrowband ultrasonic spectroscopy (NBUS) is likely to increase rapidly with the growing application of layered structures in modern aircraft, for example, GLARE. The aim of this paper is to enlighten the potential and the limitations of the NBUS techniques. Operation of the NBUS technique based on the measurements performed using a specially designed resonance transducer with carefully selected narrow frequency band is explained in detail. Novel method based on the use of impedance plane for sensing transducer resonance is presented. Theoretical results illustrate the relation of the impedance plane indications to the adhesive strengths in aluminum sandwich structures. Finally, practical application of the proposed technique on mechanized inspection of carbon fiber reinforced structures is presented.

Introduction: Ultrasonic resonance spectroscopy (URS) utilizes information in the frequency domain obtained due to the constructive and destructive interference of elastic waves for nondestructive evaluation of inspected objects. In a resonance test an ultrasonic tone-burst with sweeping frequency is applied to an ultrasonic transducer and a resonance spectrum of the inspected structure is acquired, [1]. The acquired spectrum contains information about the properties of materials used for the structure and flaws that may be present in it. Generally, there are two types of resonance test, global and local. Global tests provide synthetic information about the entire inspected part, and therefore, can be applied to relatively small parts where vibrations can be excited in the whole inspected volume. Local tests are more suitable for aerospace structures, where local structure condition is of interest, and only a selected part of the structure is excited.

Ultrasonic resonance spectroscopy has been used for the inspection of aerospace structures and its application field is expected to increase rapidly with the growing application of layered structures in modern aircraft (e.g. GLARE that is a structure material used for the A380 from Airbus). However, the new applications compel increased demands on the RI instruments and transducers in terms of their sensitivity and their ability to characterize defects. Unfortunately, very limited information concerning the operation principles of the commercially available RI instruments is available in the literature.

A fundamental limitation of resonance inspection is its sensitivity to factors that are unessential for the test, such as, variations in dimensions or material properties that may mask the effect of smaller defects. This problem can be solved either by modeling or, when modeling is unfeasible by employing sophisticated self-learning algorithms for tuning parameters of the defect detector. In the case of multilayered aerospace structures modeling seems to be the most suitable solution.

The purpose of the present paper is to fill this gap and to enlighten the potential and the limitations of the URS techniques. The presented material is a result of our research aimed at development of narrowband ultrasonic spectroscopy (NBUS) capable of coping with new applications and the increased demands. We start from explaining NBUS principles for multi-layered structures and presenting a model enabling simulation of the tested structure and transducer. Finally, we present a new solution to the sensor problem based on measuring its electrical impedance.

Measurement setup: Narrowband ultrasonic spectroscopy has been used for the NDE of aerospace multi-layered structures since 70-ties. Commercially available instruments (bond testers) used for this test operate on the principle of exciting a mechanical resonance in a multi-layered structure. A piezoelectric probe, excited by a swept frequency signal is coupled to the surface of the inspected structure using a coupling agent (see Fig. 1). The instrument acquires probe's frequency spectrum in the range of some tens of kHz to several hundreds of kHz. A resonance in the layered structure occurs when echoes between two boundaries travel back and forth due to the difference in acoustic impedances at the boundaries. For multi-layered structures, a number of resonance modes can be observed depending on their geometry and condition. A characteristic resonance pattern, an ultrasonic signature, obtained for each particular defect-free structure and given transducer can be used as a reference.
It is worth to mention that the probe characteristics are crucial for the NBUS test since shift of its resonance frequency indicates condition of the inspected structure. Therefore highly resonant piezoelectric probes are preferred for this kind of test. Serious difficulties can be encountered when applying NBUS to attenuating materials, like carbon fiber reinforced composites (CFRP). Resonance of a probe coupled to such structure is not only shifted in frequency but also spoiled in the sense that the resonance peak becomes broad and the resonance frequency cannot be detected accurately.

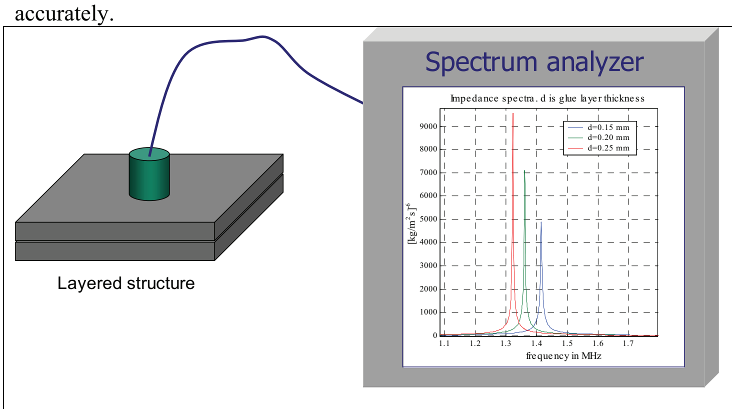

Figure 1. Principle of the narrowband ultrasonic spectroscopy test of a layered structure.

In classical NBUS inspection of an unknown object (for instance, using *Fokker Bond Tester*) its surface is scanned using a suitable probe and the resulting ultrasonic spectrums are acquired for a number of frequencies. Debond detection is performed by an operator observing simple features of the acquired spectra, such as, center frequency and amplitude of the highest peak in a pre-selected frequency range. This means that the operator has to perform the spectrum classification task based on primitive features extracted by the instrument. Below, we present models that explain this principle.

Structure modeling: A software tool was developed for calculating the input acoustical impedance of sandwich structures consisting of a number of semi-infinite parallel layers. Material constants, such as density and sound velocity are used as parameters. The software, which is written in Matlab™ uses a model based on the transmission line concept for recursive calculation of the impedances seen from the top of the successive layers. It is assumed that a longitudinal plane wave is incident on the structure's top boundary, details can be found in [2], [6] and [7]. Material attenuation can be included in the model.

Assuming that acoustical impedances and thicknesses of the individual layers are known the model implemented in the toolbox calculates the impedance of the multi-layered structure. The model is valid for longitudinal plane waves only.

The software has been used for simulating laminated airspace structures consisting of aluminum layers bonded by adhesive layers. Spectral variations due to debonds and voids between the aluminum plate and the adhesive can be modeled and evaluated. As an example, Fig. 2 shows results obtained for a simple laminated structure consisting of two aluminum plates (top 1.27 mm and bottom 1.0 mm) bonded with 0.2 mm adhesive.

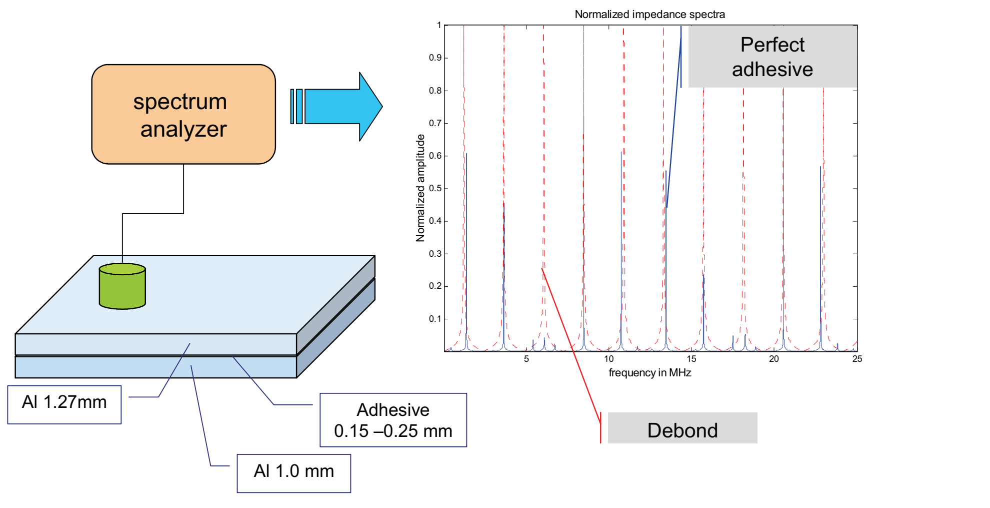

Figure 2. Multilayered Al structure and its simulated acoustic impedance.

Debonds would be relatively easy to detect if variations in the spectra measured for a defect free structure (*nominal spectra*) were small. Unfortunately, variations of the adhesive parameters (mainly its thickness) may result in quite large shifts of the resonance peaks.

Transducer modeling: A narrowband, piezoelectric low frequency transducer (below 1 MHz) is a vital part of the NBUS setup. Since the transducer is undamped, it has a distinct frequency peak corresponding to its thickness mode (cf. [3]).
Piezoelectric transducers are electromechanical systems that can be modeled in many ways depending on the application. Here, the KLM model [4], based on the transmission line concept was chosen since it enables modeling the transducer under various load conditions. In the KLM model the acoustical side (a transmission line of a length *d*) is coupled to the electrical side by a transformer with ratio ($1{:}\phi$) (see Fig. 3). The transmission line has two ports where acoustical loads are applied, the backing at the left-hand side and the inspected structure at the right-hand side. Thus, the influence of acoustical load variations on the transducer's electrical impedance can be modeled.
In other words, when a piezoelectric transducer is used for inspecting a multi-layered structure, as shown in Fig. 3, the structure's acoustical impedance can be directly plugged

into the KLM model and the electrical impedance of the transducer calculated using this model will reflect variations in the inspected structure.

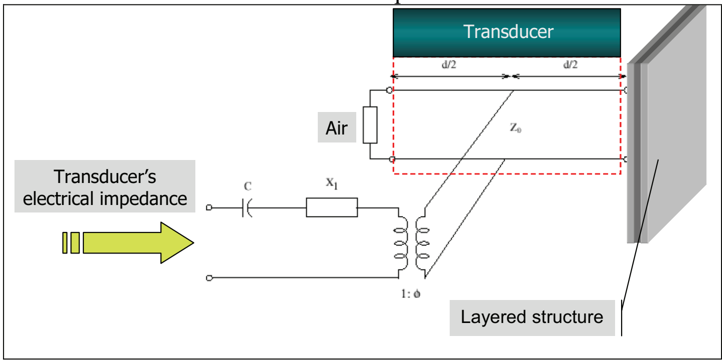

Figure 3. KLM model of a piezoelectric transducer coupled to a multilayered structure.

Before this can be done parameters of the transducer model have to be estimated using an adequate procedure. Fig. 4 shows as an example results obtained for a simple piezoelectric transducer (PZT cylinder with diameter approx. 13 mm and thickness 25 mm). The electrical admittance of this element, measured using the *4395A Network/ Spectrum/Impedance Analyzer* from *Agilent Technologies* is shown in Fig. 4 together with the results obtained from the KLM model. Parameters of the KLM model corresponding to the transducer were estimated from the *Analyzer* measurements using an identification procedure described in [6]. A very good agreement between the measurements and simulations was obtained, which is not surprising for an undamped transducer in air.

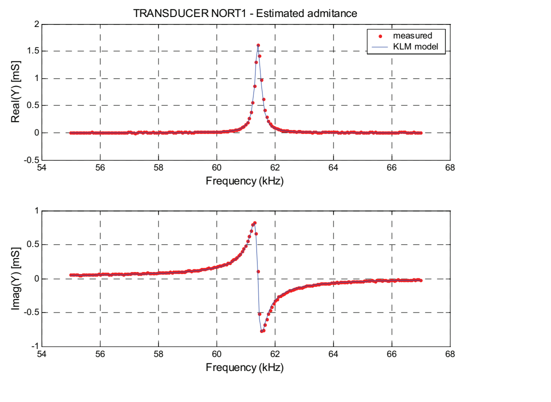

Figure 4. Results of the KLM model parameters estimation. Measured values of transducer's admittance (dots) and admittance of the KLM model (solid line).

When the transducer is loaded with an acoustic load (e.g. it is coupled to a multi-layered structure) its spectrum changes depending on the acoustic impedance of the load and the resonance frequency shifts slightly. These changes can be detected if the transducer is excited with a swept frequency signal and its electrical impedance measured in some frequency band is displayed for an operator.

An attempt was made to use an electronic circuit employing a phase locked loop (PLL) circuit for detecting resonance frequency of a piezoelectric resonator. The automatic detector was tested on triple-layered Al structures with artificial debonds, the results were presented in [6] and [7]. The measurements and the simulations have shown a significant difference between the resonance frequencies corresponding to lower and upper debonds in Al structures. The above-presented software tool enabled maximizing this difference appropriately to the type of structure by the choice of frequency band optimal for the applied transducer. However, sensitivity of this method was sufficient neither for the evaluation of weak bonds produced in Al samples nor for detecting defects in CFRP.

Poor results obtained in the demanding applications motivated the development of a new method based on sensing transducer's complex valued impedance for a single, carefully selected frequency.

Variations of the transducer impedance: Transducer impedance is a complex number that can be represented as a vector in a complex plane. Modeling results have shown that transducer impedance measured for some frequency close to its resonance underlies considerable variations depending on condition of the inspected material.

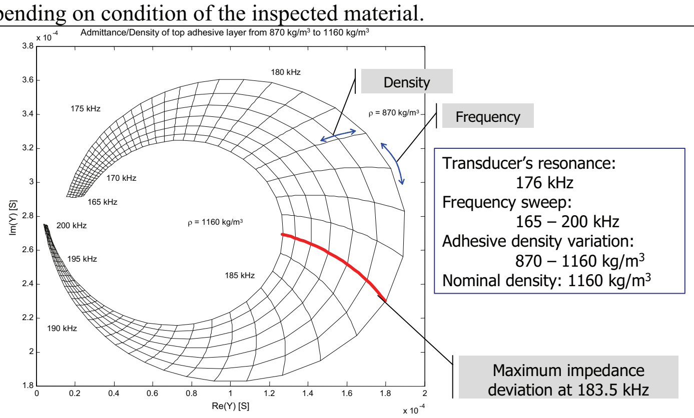

Figure 5. Variation of transducer impedance as a function of adhesive density ρ and frequency f.

When the inspected surface is scanned using a piezoelectric probe coupled to the inspected structure the impedance vector in the impedance plane moves providing additional information, like in eddy current inspection.

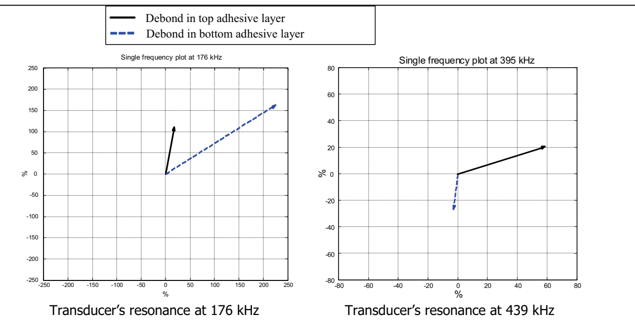

Figure 6. Variation of transducer impedance corresponding to debonds in triple-layered Al-plate

An example of impedance variation for the Fokker probe used in the above-mentioned experiment (cf. Fig. 2) in function of adhesive mass density ρ for the test frequencies in the interval from 165 to 200 kHz is shown in Fig. 5. Frequency change moves the operating point along an arc while the increase of mass density moves it towards the coordinate origin. An example of impedance analysis is presented in Fig. 6 for a triple-layered Al structure with two adhesive layers, upper and lower. Transducer responses to debonds in the adhesive layers are shown for two operating frequencies. It is apparent that both debonds can be distinguished based on their responses in the impedance plane, however, at higher frequency (395 kHz) an angle between the indications is larger (at the price of a reduced magnitude). Similarity to the variation of coil impedance in eddy current testing is apparent.

It should be noted that the *Bond Master* from *Staveley NDT Technologies* probably implements the principle similar to that presented here. Our modeling tool makes possible the systematic investigation of how different structure parameters (such as, debonds, adhesive strength) effect transducer impedance and in this way enables an optimal choice of a suitable probe and its test frequency with respect to the inspected structure. Below, we present some experimental results obtained in CFRP inspection.

Inspection of CFRP specimens: Mechanized inspection of CFRP samples was performed using an XY-scanner, computerized impedance measuring instrument and a PZT transducer operating at frequencies in the range of 1 MHz. The transducer had diameter 0.5" and was fed with a single frequency sine wave with

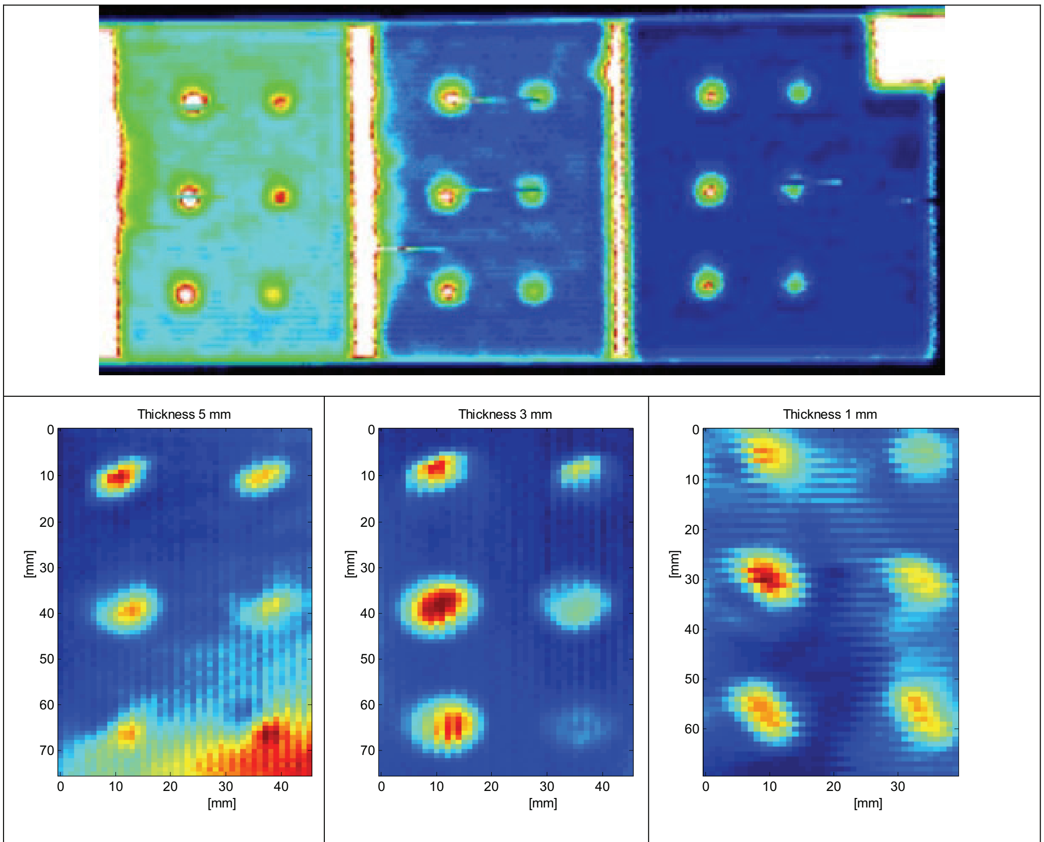

Figure 7. Inspection results obtained for the step-wise specimen of CFRP. Ordinary ultrasonic C-scan obtained in through transmission (upper panel) and C-scans obtained using the proposed method (lower panels).

amplitude approx. 10 $V_{p\text{-}p}$ and its complex impedance measured in discrete XY-points was stored in a PC.

A complex valued C-scan obtained in this way was displayed directly at the PC's screen. A small volume of water applied on the inspected surface was used to obtain contact between the transducer and the inspected structure. A step-wise specimen with variable step thicknesses (1, 3 and 5 mm) was inspected. In each step 6 artificial defects were manufactured to simulate delaminations, see Fig. 7. The defects manufactured at each step have two sizes, 6 x 6 mm (left column) and 4 x 4 mm (right column in Fig. 7). The defects in each column were located at different depths, in the lower row in Fig. 6 are the defects located at the depth of two plies from the upper surface, in the upper low are the defects located at two plies from the lower surface, and the middle row represents defects in the middle of step thickness.

The results are shown in Fig. 7 together with the ultrasonic C-scan obtained in transmission inspection as a reference. It is evident that the proposed method is capable of detecting almost all defects in the inspected specimen; the most difficult seems to be detecting shallow defects in the thick section of 5mm. It should be noted however, that the presented results are preliminary and that the probe used in the experiments has not been optimized for this purpose. Nor have any attempts yet been made to improve SNR by averaging or other signal processing methods.

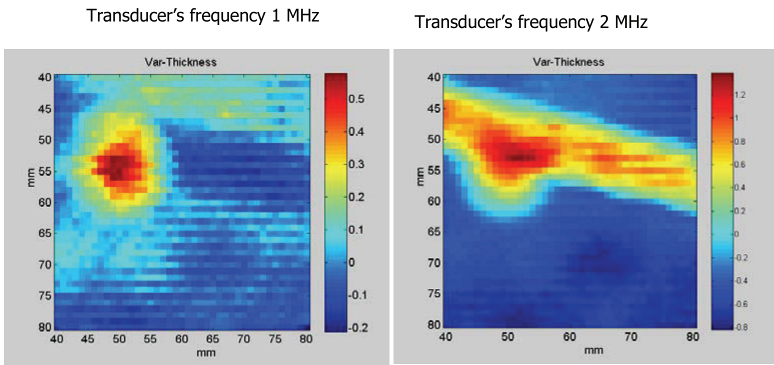

Figure 8. Inspection results obtained for a CFRP specimen with impact and local variation in thickness at two frequencies, 1MHz (left) and 2 MHz (right).

The effect of test frequency is illustrated by an example shown in Fig. 8 presenting results of the inspection of a CFRP specimen with an impact. The inspection was performed using a broadband transducer operating at two frequencies, 1 MHz and 2 MHz, respectively. Both C-scans in Fig. 8 correspond to the same area of the specimen. An impact in the specimen is well pronounced at the upper-left corner of the C-scans at both frequencies. However, the inspected specimen had local variation in thickness taking the form of a line with increased thickness. This line can be easily seen at the right hand C-scan acquired at 2 MHz.

Summary and conclusions: Feasibility of different URS set-ups in application to aerospace structures has been investigated and the narrowband spectroscopy (NBS) has been selected as the most promising candidate. The method based on tracing resonance frequency of a resonant transducer using a PLL circuit was developed and examined. It appeared that its sensitivity in more demanding applications was unsatisfactory. An alternative method based on sensing probe's electrical impedance was developed and verified using CFRP specimens with artificial and natural defects.

NBS tests of layered structures performed using a narrowband transducer require proper choice of transducer and its resonance frequency. Today, this choice is performed ad hoc, based on operator's experience and some recommendations from the instrument manufacturer. The theoretical model of the multi-layered structure including the piezoelectric transducer presented in the paper makes this choice much easier and enables maximization of the transducer indication with respect to the parameters of the inspected structure. The model enables accounting for the effects of natural variations in dimensions and material properties as well as optimizing sensitivity of the NBS transducer to defects. Simulation results obtained using the presented model were used to explain the principle of narrowband inspection of multilayered structures. The simulation results were verified by measurements performed using a network analyzer.

Preliminary mechanized tests performed on selected specimens yielded very promising results; the proposed method was capable of detecting artificial delaminations in CFRP of different thicknesses as well as natural impact defects.

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