ELSEVIER

Ultrasonics 36 (1998) 343–348

Ultrasonics

Numerical modeling of the effects on reflected acoustic field for the changes in internal layer orientation of a composite

Aziz-Ur Rehman [a,*], Catherine Potel [a,b], Jean-François de Belleval [a]

[a] *Laboratoire de Génie Mécanique pour les Matériaux et les Structures (UPRES ass. CNRS), Université de Technologie de Compiègne, Division Acoustique, BP 20529, 60205 Compiègne Cedex, France*
[b] *Université Picardie Jules Verne, IUT Amiens, Dept. OGP, Soissons, France*

Abstract

Acoustic propagation through anisotropic multilayered media has become a subject of intensive study, because of its application to nondestructive evaluation, geophysics etc. We consider the multilayered media created by stacking distinct anisotropic layers. A very interesting case of multilayered media is that of the composite material, in which we have different layers with different orientations from one another. A realistic calculation of reflected ultrasonic beam patterns from these composites requires treatment of the effects of refraction and reflection from finite and infinite media. Application of the angular spectrum analysis (ASA) to calculate the acoustic fields has become increasingly adopted, because the ASA is easy to be numerically implemented upon the basis of the Fast Fourier Transform and can be used effectively to solve the variety of complex problems.

The developed numerical model can be applied to determine the effects of changes in orientation of the layers in a composite material on the reflected acoustic field. Here we compare the results for different layer orientations in a carbon/epoxy composite. From this it can also be concluded, with better reliability, that when using multilayered composites it is essential that the internal construction fulfils the specifications exactly, because the changes in internal layer orientation can change totally the characteristics of that composite due to the fact that the elastic characteristics of the composite medium depends also on the orientation angle of the internal layers. Moreover, in using this method, we can detect the changes in orientation of the internal layers, and their effects on the acoustic fields through/from the composites. © 1998 Elsevier Science B.V.

Keywords: Composites; Ultrasonic interaction; Angular spectrum analysis; Multilayered anisotropic structures; Nondestructive evaluation

1. Introduction

Multilayered composite materials are being used extensively in aircraft, naval, aerospace and automobile industries mainly because they allow designers to achieve very important strength-to-weight and stiffness-to-weight ratios when compared with traditional materials. The design process of such types of structures is specifically dependent on the number of layers to be used, the thickness of each layer, and the orientation angles of the fibers in each ply [1]. The mechanical properties of a composite are strongly dependent on the fiber directions and, because of that, the composite should be designed to meet the specific requirements of each particular application in order to obtain the maximum advantages of such materials.

It is important to many manufacturing industries that adequate non-destructive testing methods are devised for the inspection of multilayered fibrous composites. Despite the large amount of research conducted, there is still concern that some types of defects may be difficult to detect in multilayered composites [2]. Although some of these defects may not lead to a significant reduction in the mechanical strength of a composite specimen, their presence may complicate signals from conventional ultrasonic inspection methods, or may lead to, e.g., confusing conclusions. Considerable research is therefore underway to improve on conventional ultrasonic techniques, often through the use of lamb wave methods. As part of such a research program, a numerical model for wave propagation within layered anisotropic plates has already been developed, to understand the behavior of ultrasonic waves within composite materials [3–5], and to study the sensitivities of these waves to defects

---

* Corresponding author: Tel.: (33) 34423 4423, ext: 4705 or 4726; fax: (33) 34423 5287; e-mail: aziz-ur.rehman@utc.fr

0041-624X/98/$19.00 © 1998 Elsevier Science B.V. All rights reserved.
PII S0041-624X(97)00084-X

like internal layer mis-orientation. Here, we intend to apply the angular spectrum decomposition to extend the existing numerical model to investigate the effects on the reflected acoustic field for the changes in the internal layer orientation of a multilayered fibrous composite.

The model for multilayered fibrous composites, and some preliminary applications, are presented in this paper. The next section summarizes the existing models for wave propagation in anisotropic layered materials, and puts the current model into context relative to this earlier work. The model is then outlined, and conclusions are drawn in the final section.

2. Summary of existing literature

There have been numerous theoretical and numerical investigations of the propagation of ultrasonic waves in layered anisotropic plates, and it would be impossible to present here a summary of all this work which would do justice to all of the contributors. However, much of the work may be summarized by reference to a sample of the literature.

Analytical solutions to the problem of plane wave reflection from layered plates may be obtained for some special situations, such as a plate composed of a single layer, with the plate surface a material plane of symmetry, or for a multilayered plate with symmetry restrictions for each layer [6]. In general, numerical solution of the resultant equations is necessary, because of the algebraically complicated nature of the expressions involved. The most popular method for numerical solution is through the so-called transfer matrix method. The solution in the layer to be considered is known through a matrix equation, involving the solution in the previous layer [3–5,7]. This matrix equation is obtained by writing the boundary conditions at the interface between two successive layers. The solutions themselves are in the form of a vector with components given by the displacements and stresses within the layer. By repeated application of the transfer matrices, the solutions within all the layers are determined from the known incident wave.

Most of the above model considers plane wave theory, which is not usually adequate for realistic non-destructive inspection situations where finite-sized transducers are employed. The incident wave will contain a range of angles, the sensitivity of the receiver will be directionally dependent, and the incident wave may be a short pulse. Plane wave theory therefore needs to be incorporated into a bounded-beam model, usually through integration over the plane wave spectrum through the use of Fourier transform techniques [8–12].

Another consideration needed for realistic applications of any model to composite materials is the relatively high levels of attenuation encountered in these materials [13]. Any model that takes this into account usually shows considerably improved agreement between theory and experiment, for quantities such as the reflected wave fields.

The model presented here is similar in principle to many of the models mentioned above, but with some extensions. Layers within the plate are anisotropic solids and attenuation is also taken into account. The model does, however, differ from those other models which also include full anisotropic attenuation with the layers [4,5,7] by considering the bounded nature of the incident beam, and the angular dependence of the receiver sensitivity.

3. Problem formulation

We consider the case of a multilayered fibrous composite immersed in water. Referring to Fig. 1 for the definition of coordinates, and it will be assumed that the plate's upper surface forms the xy plane, and the xz plane is the plane of incidence. An ultrasonic beam of width $2a$ and an angular frequency $\omega = 2\pi f$ is seen to be incident at an angle θ_i on a fluid-loaded multilayered anisotropic solid plate. The emitting plane is taken at O in the fluid region and the Gaussian normal velocity distribution along this plane transducer is assumed. In the context of angular spectrum analysis, an acoustic beam can be represented as being composed of an infinite number of plane waves, all of the same wavelength but at different incident angles with respect to the normal to the emitting plane. It is shown [8–11] by using Fourier analysis that the field of an incident beam can be uniquely determined at any point, if its field distribution is known in any plane.

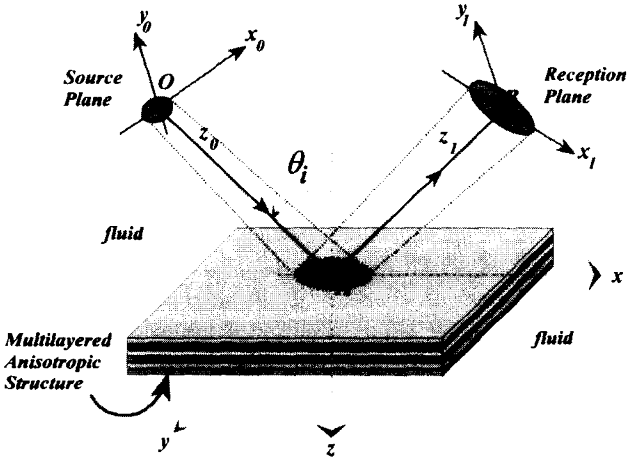


Fig. 1. The geometry of the problem to be studied. A transmitter and receiver are located above the plate, with there beam axes defined by the incident angle θ_i. The beam axes are assumed to be within the same plane. The transmitter and receiver axes are not necessary aimed at the same point on the plate.

The interpretation of angular spectrum analysis is extended to the ultrasonic field reflected by the multilayered anisotropic plates by using the exact angular dependent reflection coefficients for individual plane waves and incorporating them in the Fourier integrals. The reflection of acoustic beams has been thoroughly studied by many authors and here we are extending their treatments to look for the effects of internal layer orientation on the reflected acoustic fields from the multilayered composites.

4. Configuration of composite

Let us consider an anisotropic periodically multilayered medium which is a reproduction of two superlayers, each one is made by stacking four distinct layers of carbon/epoxy having the volumetric mass of 1577 kg m^{-3} (see Fig. 2(a)), each layer is 0.13 mm thick and being at 45° to the previous. The elastic properties of the carbon/epoxy layer are given in Table 1. The wave attenuation is taken into account by a complex definition of elastic constants [13]. From experimental results on these kinds of materials, the imaginary part of these elastic constants can be considered as independent of the frequency for the range of 0.5–6.0 MHz [3,7]. In Fig. 2(b) another configuration is shown, which is slightly different from that of Fig. 2(a), in a sense that the internal layer orientations of the 2nd superlayer are slightly different from that of the first. We can presume here that the first layer of the 2nd superlayer is placed incidentally in the wrong orientation.

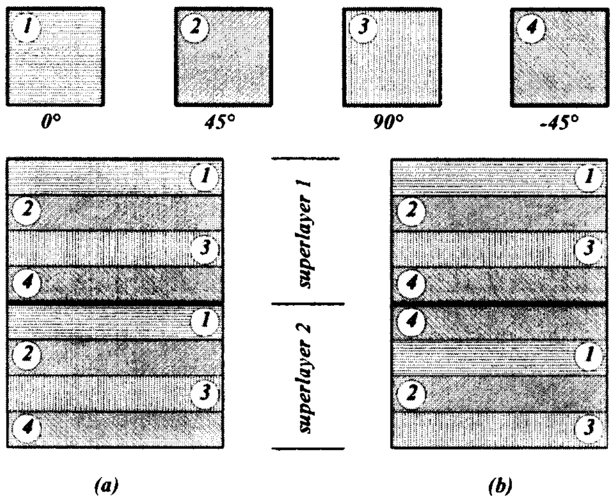


Fig. 2. The configuration of the multilayered fibrous material. (a) The plate consists of two superlayers of [0°/45°/90°/−40°] carbon/epoxy having the thickness of 0.13 mm per layer. (b) The plate consists of same number of layers having identical material characteristics, with a difference of internal layer orientations in the 2nd superlayer.

5. Plane wave reflection coefficients

It was described [5] that, by writing the boundary conditions at each interface separating two successive layers, the transfer matrix of one superlayer can be found, which allows the displacement amplitudes of the plane waves in the first layer of a superlayer to be expressed as a function of those in the first layer of the next superlayer. Due to the fact that, locally, the acoustical state is characterized by six quantities, this matrix is of the 6th order, and the waves which correspond to the eigen vectors of this matrix are Floquet waves. If the general solution is decomposed on the Floquet wave basis, the transfer matrix becomes a diagonal matrix. These six Floquet waves are the propagation modes of an infinite periodically multilayered medium. They are linear combinations of the classical waves propagating in each layer of the multilayered medium and the linear combination differs simply according to the layer [3,5].

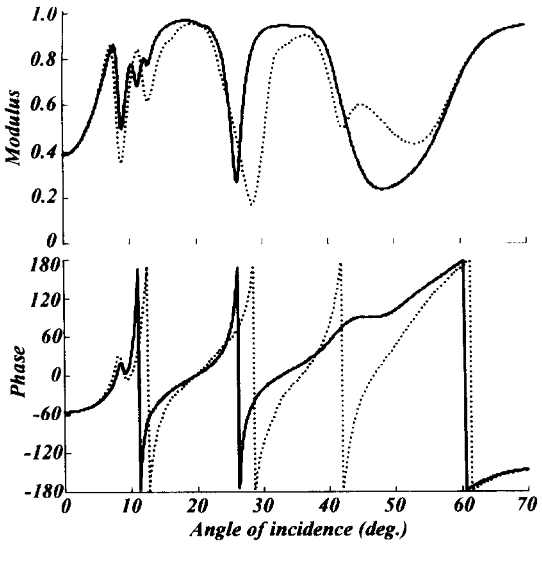


Fig. 3. Calculated modulus and phase in degrees of plane wave reflection coefficients for (———) the configuration having two superlayers compared with (· · ·) the configuration having different internal layer orientations in the 2nd superlayer at an incidence frequency of 3.0 MHz.

Table 1
Elastic constants used in the model (from Ref. [3]). Elastic constants are in GPa, and the composite density is taken to be 1577 kg m^{-3}

C_{11}	C_{12}	C_{13}	C_{33}	C_{44}	C_{66}
13.7+0.13 j	7.10+0.04 j	6.7+0.04 j	126.0+0.73 j	5.8+0.73 j	3.30+0.05 j

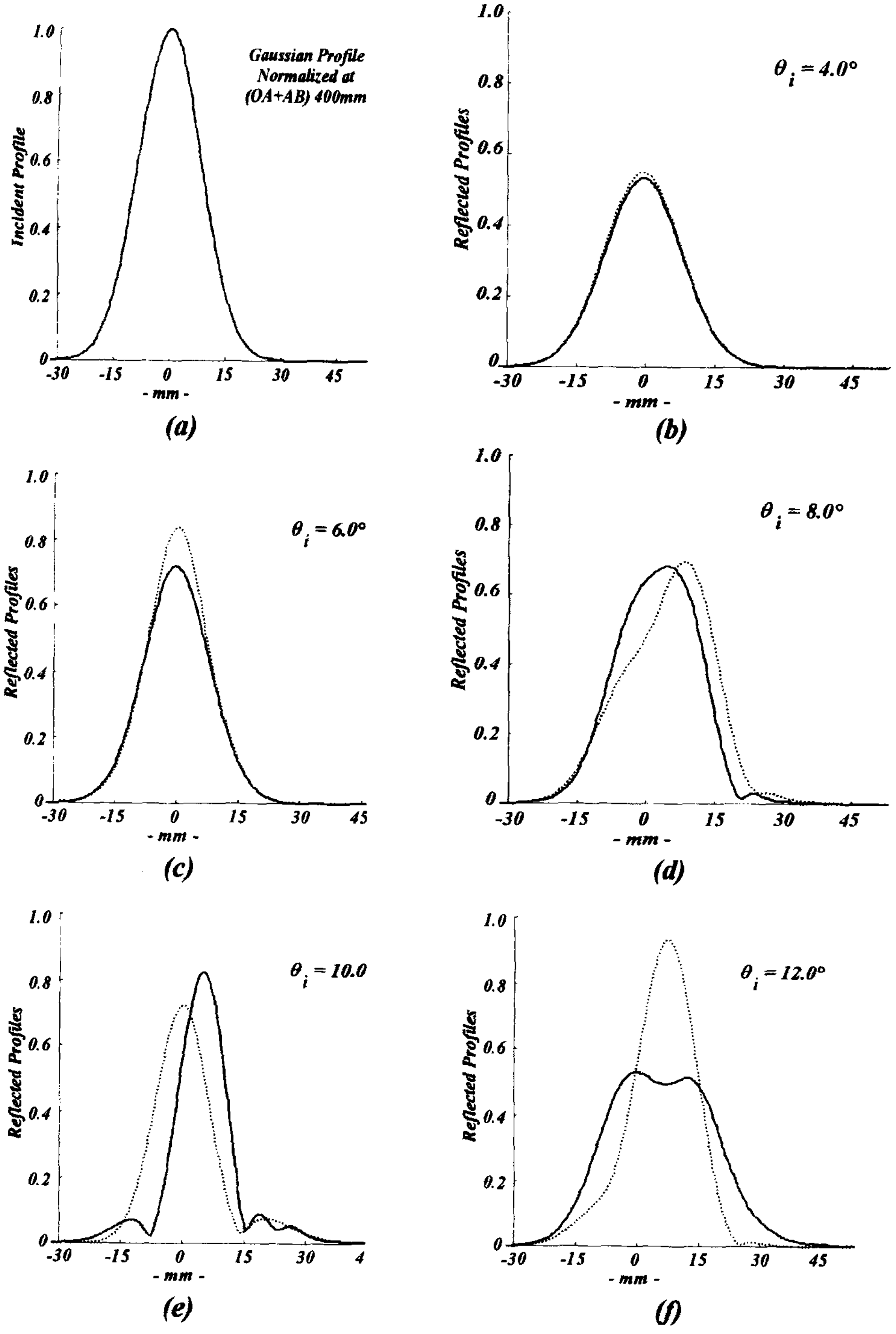


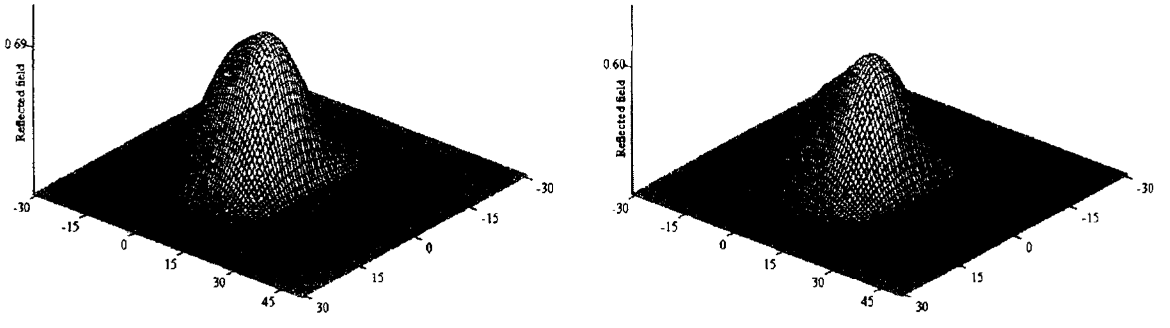
Fig. 4. Calculated two-dimensional reflected profiles, normalized at (OA + AB = 400 mm) observation plane for (———) the configuration having two superlayers compared with (· · ·) the configuration having different internal layer orientations in the 2nd superlayer.

The amplitude plane wave reflection coefficients as well as the changes in phase for the cases of interest, i.e. for a medium consisting two periods of {0°/45°/90°/−45°} carbon/epoxy plate and for a medium consisting of eight layers of {0°/45°/90°/−45°/−45°/0°/45°/90°} carbon/epoxy (Fig. 2(a),(b)) at an incidence frequency of $f = 3.0$ MHz, are shown in Fig. 3.

6. Reflected profiles for incident gaussian beam

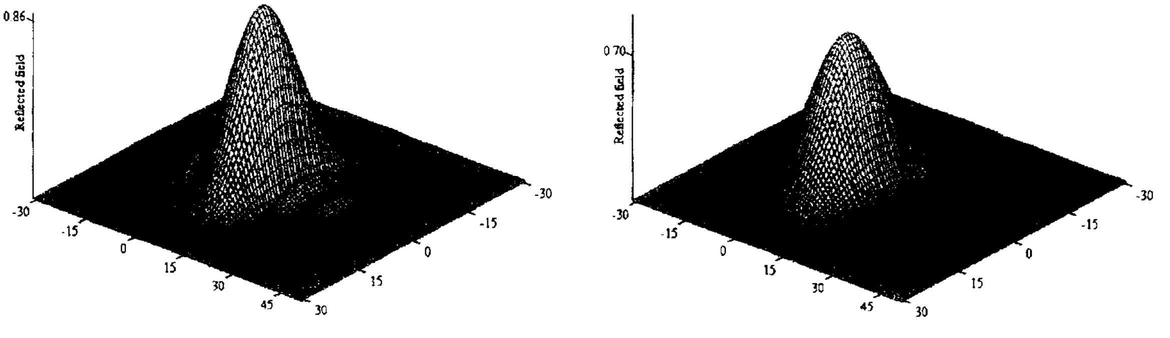
The angular spectrum decomposition method is then applied to study the reflected beam profiles from a multilayered anisotropic structure immersed in a fluid. The incident frequency is fixed at $f = 3.0$ MHz and the diameter of the incident Gaussian beam is taken to be

12.7 mm, the profile of which is shown in Fig. 4(a). Fig. 4 also shows the comparisons of reflected profiles for both material configurations at several incident angles for the transducer normal distance 200 mm (OA). As the problem is of three-dimensional nature, the three-dimensional reflected acoustic fields are also compared for both material configurations (Fig. 5). It is worth noticing here that if the calculations are done on or about the normal incidence (i.e. around $\theta_i = 0°$) then we have no major difference between the reflected acoustic field for both configurations, and the more we move away from the normal incidence, the more we see the differences in the reflected fields for both configurations. The difference in material configuration changes the effective path length of the waves traveling across the multilayered fibrous composite, which modifies the



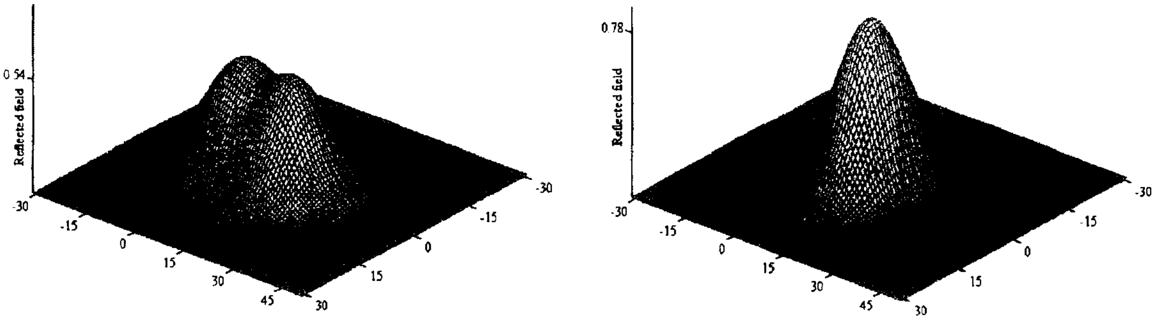
(i) *(ii)*

a. Reflected profiles for an incidence of 8.0°.



(i) *(ii)*

b. Reflected profiles for an incidence of 10.0°.



(i) *(ii)*

c. Reflected profiles for an incidence of 12.0°.

Fig. 5. Calculated three-dimensional reflected profiles, normalized at (OA + AB = 400 mm) observation plane for (i) the configuration having two superlayers of identical internal structure compared with (ii) the configuration having different internal layer orientations in the 2nd superlayer.

reflection characteristics (amplitudes and phase changes). With the change in configuration, the minima in the reflection amplitudes and the position of the Leaky Modes (Lamb and Multilayered Rayleigh Modes) changes, and as a result we see their influence on the reflected acoustic fields from both configurations (Fig. 4(c)–4(f)). As it was extensively explained in Ref. [3], the propagation of what has been called Multilayered Rayleigh Mode is both characterised by the cancellation of 3 × 3 determinant and an inhomogeneous character of all the Floquet waves which propagate in an infinite anisotropic periodically multilayered medium. The major difference between the propagation of Rayleigh wave in an isotropic medium and the propagation of Multilayered Rayleigh wave in an anisotropic stratified medium is that the first one is not dispersive whereas the second one is linked to both an angle and a frequency. It is also shown [3], that there exists a higher-order multilayered Rayleigh mode at about 16° for a configuration of six superlayers, is also evident in our case (see Fig. 3). However, with the change in configuration, the mode changes its position (angle of incidence), and the effects can be seen on the reflected acoustic field, if the multilayered composite is insonified at the same ultrasonic incidence. As the incident beam is well-collimated and the higher-order mode for both these configurations are apart, we see a very noticeable difference in the ultrasonic reflected profiles from both configurations for an incidence of 12° (Fig. 4(f)). Since the ultrasonic beam is characterised by a broad angular spectrum, and at that incidence, the beam angular range encompass the reflection minima, corresponding to the leaky modes.

We can conclude from these results that for normal incidences, the modes are not apparent, except possibly at low frequencies. Therefore, by increasing the angle of incidence, the shear component within the plate increases, the modes start appearing, and the effects on the reflected acoustic fields for both configurations become more and more visible.

7. Conclusion

Here a model is presented for calculating the behavior of ultrasonic waves in multilayered fibrous composites. The model allows to take into account the effects of finite transducer size in calculating the reflected profiles from a multilayered fibrous composite in ultrasonic immersion testing. The model also accounts for the presence of attenuation and the internal fiber orientations in calculations.

Sample results from the model have been presented showing how the leaky modes (Lamb and Multilayered Rayleigh Modes) within the plates are modified with the changes in internal layer orientations. The potential use of the model predictions helps in calculating and devising the methods for detecting the presence of these type of changes in prescribed configurations, and to estimate the correct testing angles for the transducer placement.

References

[1] J. Denault, T. Vu-Khanh, B. Foster, Tensile properties of injection molded long fiber thermoplastic composites, Polymer Composites 10 (1989) 313–321.

[2] Y. Bar-Cohen, R.L. Crane, Nondestructive evaluation of fiber reinforced composites with acoustic back scattering measurements, Materials Evaluation 40 (1982) 970–975.

[3] C. Potel, J.F. de Belleval, E. Genay, Ph. Gatignol, Behavior of Lamb waves and multilayered Rayleigh waves in an anisotropic periodically multilayered medium: Application to the long-wave length domain, Acta Acustica 82 (1996) 738–748.

[4] C. Potel, J.F. de Belleval, Y. Gargouri, Floquet waves and classical plane waves in an anisotropic periodically multilayered medium: Application to the validity domain of homogenization, J. Acoust. Soc. Am. 97 (1995) 2815–2825.

[5] C. Potel, J.F. de Belleval, Propagation in an anisotropic periodically layered medium, J. Acoust. Soc. Am. 93 (1993) 2669–2677.

[6] D.E. Chimenti, A.H. Nayfeh, Ultrasonic reflection and guided wave propagation in biaxially laminated composite plates, J. Acoust. Soc. Am. 97 (1990) 1409–1415.

[7] B. Hosten, M. Castaings, Transfer matrix of multilayered absorbing and anisotropic media. Measurement and simulations of ultrasonic wave propagation through composite materials, J. Acoust. Soc. Am. 94 (1993) 1488–1495.

[8] A.-U. Rehman, C. Potel, J.F. de Belleval, Modeling of ultrasonic beam interaction with an anisotropic multilayered medium, using angular spectrum method, 23rd International Symposium on Acoustical Imaging, 13–16 April 1997, Boston, MA.

[9] H.L. Bertoni, T. Tamir, Unified theory of Rayleigh-Angle phenomena for acoustic beams at liquid–solid interfaces, J. Appl. Phys. 2 (1973) 157–172.

[10] L.E. Pitts, T.J. Plona, W.G. Mayer, Theory of nonspecular reflection effects for an ultrasonic beam incident on a solid plate in a liquid, IEEE Trans. Sonics Ultrason. 24 (1977) 101–109.

[11] T.D.K. Ngoc, W.G. Mayer, General description of ultrasonic nonspecular reflection and transmission effects for layered media, IEEE Trans. Sonics Ultrason. 27 (1980) 229–236.

[12] J.M. Claeys, O. Leroy, Reflection and transmission of bounded beams on halfspaces and through plates, J. Acoust. Soc. Am. 72 (1982) 585–590.

[13] B.A. Auld, Acoustic Fields and Waves in Solids, John Wiley & Sons, New York, 1990.