# Guided Waves in Layered Plate with Delaminations

Fabrizio Ricci, Ajit K. Mal, Ernesto Monaco, Leandro Maio, Natalino Daniele Boffa, Marco Di Palma, Leonardo Lecce

# GUIDED WAVES IN LAYERED PLATE WITH DELAMINATIONS

[1]Fabrizio Ricci, [2]Ajit K. Mal, [1]Ernesto Monaco, [1]Leandro Maio,
[1]Natalino D. Boffa, [1]Marco Di Palma, [1]Leonardo Lecce

[1] *Industrial Engineering Dept., University of Naples "Federico II", Naples, Italy*
[2] *Mechanical and Aerospace Engineering Dept., University of California, Los Angeles, USA*

*e-mail: fabricci@unina.it*

## ABSTRACT

The integrity of safety-critical structural composites can be enhanced by the use of innovative ultrasonic nondestructive evaluation (NDE) techniques. Among the various existing techniques, guided wave methods provide a good compromise in terms of sensitivity to a variety of damage types or defects and extent of the area that can be monitored, given the ability of this waves to travel relatively long distances within the structure under investigation. In comparison with Lamb waves propagating in isotropic structures, wave propagation in composite structures presents additional complexity for effective damage identification. The material inhomogeneity, the anisotropy and the multi-layered construction lead to the significant dependence of wave modes on laminate layup configurations, direction of propagation, frequency, and interface conditions.

In this paper a specific structure will be analyzed with different levels of complexities as far as the wave propagation characteristics are concerned. The investigated structure is a composite stiffened plate. The work is carried out using theoretical analysis, numerical models and experimental verifications. Numerical (Finite Element) models are used for more practical cases, for which the geometric and material complexities of actual structures present practical difficulties in direct analysis of wave propagation data using theoretical constructs only.

**KEYWORDS:** *Composite materials, delaminations, guided waves*

## INTRODUCTION

Demands for improved aerospace vehicle performance have led to increased use of composite materials because of their greater specific strength and stiffness, but they are very expensive to maintain. Relative to conventional metallic materials, the failure behavior of composites is not nearly as well characterized as metals and damage may be more difficult to detect; hidden damage that can reduce the residual strength, and the detection of these damages often requires accurate and time-consuming inspections to prevent catastrophic failure. It has been estimated that almost 25% of the life cycle cost of an aircraft can be attributed to operation and support, involving inspection and maintenance [1-2]. Some examples of such damages are delaminations in composite laminates due to low velocity impacts and skin-core disbonding in sandwich structures. Delamination is the failures between plies of a composite laminate, whereas disbonding concerns the failure of the interface between two or more elements in a composite structure.

Owing to the adverse effects of delamination cracks in composite materials, it becomes important to develop a damage detection system. The necessity of the aerospace industry to reduce the cost, but to keep good safety standards has brought to the improvement of Structural Health Monitoring (SHM) applications. The objective of a SHM system is to allow an easily an low-cost detection of damages, before they reach critical levels. As the diffusion of composite materials poses relevant problem regarding damage tolerance and damage detectability, SHM is one of the most promising technique for the development of lighter, more efficient and more reliable structures. The damage identification may be performed by different techniques such as ultrasonic testing, radiographic testing, electromagnetic testing, etc. The evaluation of the state of health of a structure using ultrasonics has been demonstrated to be a very promising tool. In the case of plate-like structures Lamb waves offer an attractive cost effective tool for inspecting large structures. To generate and sense ultrasonic waves the lead zirconate titanate (PZT) ceramics are typically used. They have very good performance in Lamb wave generation and are an interesting solution for integration in the structure under test. Efficient monitoring of the structural integrity of large areas from one or few confined locations can be achieved using array of guided ultrasonic piezoelectric transducers bonded onto a structure. Lamb waves can propagate at large distance with very little amplitude loss and hence offer large-area coverage and are very sensitive to the presence of defects located in their propagation path [3]. Through the measurements of these waves, by means of a series of transducers, it is expected to identify the presence of damage, its dimension and its position. At the site structural defects, the guided waves are scattered and part of the energy is reflected towards the sensor network, making the measurements sensitive to type and size of damages. However, when a guided wave interacts with a defect, a good understanding of the effects of this interaction is required to correlate the wave behavior to the location, extension and severity of the damage. Moreover, some of the interaction features can be evaluated with laboratory experiments, but numerical simulations and analytical model, if available, can provide a better understanding at a lower cost. However, the Lamb wave based SHM approach increases the complexities in the diagnostic signal, as it is not precisely tuned and shaped. Boundary scattering is difficult to deal with, and is generally avoided in conventional NDE. The complex amplitude behavior of Lamb waves propagating in a plate shows that signal parameters based on the amplitude are not reliable for damage detection [4]. To alleviate these problems, various signal transformation techniques are developed and used in detecting damages by extracting the parametric information regarding damage from the complex signals.

Studies conducted on the interaction of Lamb wave with geometric discontinuities show the complexities involved quite clearly. Ramadas et al. [5] investigated the interaction of the fundamental anti-symmetric guided Lamb mode with T-joint in a composite structure (glass/epoxy material) through Finite Element numerical simulations and experiments. Moreover the back-propagating ''Turning modes'', which occurs in the presence of discontinuities was also numerically simulated and experimentally verified.

In general, there are two theoretical approaches to investigate Lamb waves in composites: one is exact solutions by 3-D elasticity theory, and the other is approximate solutions by plate theories. The exact solution of three-dimensional problems consisting of multilayered, angle-ply laminates of finite thickness and large lateral dimensions subjected to various types of surface loads, has been given by Mal and Lih [6] and Lih and Mal [7]. Approximate thin-plate theories have also been developed to obtain analytical solutions for the response of thin isotropic and anisotropic plates to surface loads [8].

The literature on the interaction of guided waves with cracks or other defects is much sparser. Only a handful of problems of interest in NDE of real structures have been studied to date, see, e.g. Chang and Mal [9]. The finite element method (FEM) is a versatile tool to analyze this class of problems [10] where a comprehensive approach including experimental and numerical (finite element) methods are used to determine the interaction of ultrasonic guided waves with crack like defect in an aluminum plate and a honeycomb composite sandwich plate. This paper presents an analysis of the reflections and transmissions of guided waves through layered media to explain the behavior of the guided waves when interacting with discontinuities such as delamination or disbonding. The elastic waves are generated and recorded by PZT patches.

## 1 ANALYSIS OF WAVE-DELAMINATION INTERACTION

From a practical point of view the signals acquired through an array of sensors distributed over a structure carry important information on delamination in a layered composite plate, or skin-core disbonding in a sandwich structure. However, these signals are also affected by the material

characteristics, including the level of anisotropy, rivets, stringers and geometric discontinuities (such as thickness variation) and boundaries generating scattering, diffraction and reflection of the waves.
The choice of the excitation frequency domain, as pointed out by Grondel et al. [11], is very important aspect. It's necessary to take into account three fundamentals aspects: Lamb mode number should be as small as possible to limit received signal complexity; the Lamb modes should be as non-dispersive as possible to obtain a waveform independent from the propagation distance; finally, the wavelength should be equal to or smaller than the size of the damage to be detected. To meet these requirements the dispersive curves for the group velocity must be examined. To satisfy the first requirement, only the zero-order modes, S0 and A0, should be generated. The second condition implies that, at the driving frequency, the slope of the dispersion curves should be nearly zero, so that the group velocity is almost frequency independent, and the dispersive effect of the propagation distance can be avoided. The third aspect is very important to damage detection. Elastic waves have several unique characteristics which make them suitable for SHM. One characteristic is that elastic waves can provide through-thickness interrogation, which may be of particular importance when internal defects may occur, such as in composite materials. In a real application, the size of the damage is one of the things to be evaluated, and therefore it is unknown. However, when investigating the Lamb wave method itself, the damage size is a controlled parameter, and thus it should be taken into account in order to achieve the best assessment of the NDT technique.
Attention must also be given to number of cycles. It is one of the most important parameters, because it has direct influence on the frequency content of the signal. A 5-cycle Hanning-windowed toneburst at a central frequency of 200 kHz is used as excitation and the signals received at a number of locations.

### 1.1 DISCONTINUITY IN WAVEGUIDES

By definition, a discontinuity in a waveguide is an abrupt change of the guide's characteristics along its propagation direction. Changes of cross-section, considered herein, of wall impedance, angle curvature, etc. are all examples of discontinuity in a waveguide [12]. Composite panels can be characterized by the presence of discontinuities in them related to the local change of cross-section along the panel length. The main panel discontinuities are fractures, local separations in the plane which devise two adjacent layers previously bonded and resulting, for example, from a low-velocity-impact. At these discontinuities is given the name of "delaminations" to indicate the separation between plies in a composite laminated panel. Delamination or disbond may occur due to overload or fatigue of the structure, or due to manufacturing flaws. The not-continuity between two plies influences the transmission of ultrasonic low-frequency guided wave during its propagation along the panel as an extended wave guide.

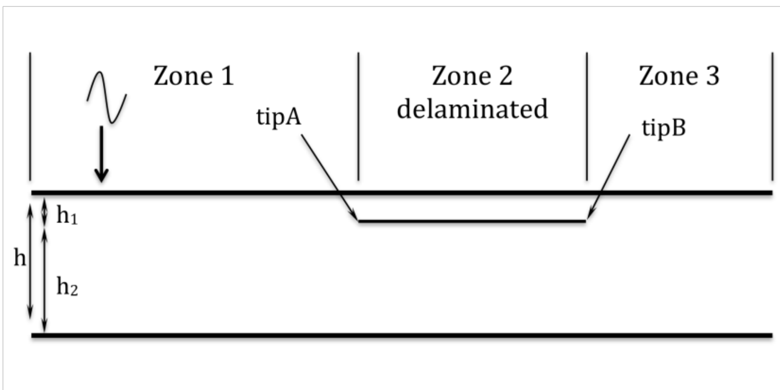


Figure 1: Sketch of a delaminated plate.

To analyze the behavior of guided waves in layered plates with delaminations or disbonding we consider a two-layered plate of total thickness $h$ containing a disbond at the interface at depth $h_1$ where $h_1 << h$. The materials of both plates are assumed to be isotropic but the analysis can be extended to anisotropic layered plates. A two dimensional model of the problem is sketched in Figure 1. The plate is divided into three zones: the elastic waves are generated at a point on the surface in *zone* 1, the defect with *tips at A* and *B* is located in *zone 2* and finally a *zone 3* where the plate is undamaged. The delamination in *zone 2* splits the plate in two sub-plates with thicknesses $h_1$ and $h_2 = h - h_1$, respectively where $h_1 << h_2$.

In order to explain the major qualitative features of the guided waves observed in our laboratory experiments presented in [10], we assume that the incident waves are of the lowest order antisymmetric ($A_0$) mode. $A_0$ mode (flexural wave) for damage identification is very useful. Its merits, in comparison with the symmetrical $S_0$ mode (the in plane or axial wave), include a shorter wavelength at a given excitation frequency, which is useful because the half wavelength of a selected wave mode must be shorter than or equal to the damage size to allow the wave to interact with the damage, and an easy way of activation; in fact, the out-of-plane motion of particles in a plate can be more easily activated.

However a low-frequency region (<1.0MHz) exists for a generic structure, antisymmetric Lamb mode, $A_0$, the symmetric Lamb mode, $S_0$ and the lowest-order shearing mode, $SH_0$.

With reference to the sketch of Figure 1, the $A_0$ waves travel undisturbed until they reach the delamination. As they encounter *tip A*, a small amount of energy is scattered by the crack tip, but most of the energy in *zone 2* travels within the thin plate of thickness $h_1$ above the disbond. Once the waves strike the second tip (*B*), a significant amount of its energy is reflected and travel backward until they reach the *tip A* and are again reflected forward. In other words the waves are trapped in the thin plate above the delamination. Although the wave-field below the delamination has a similar behavior, due to the strong attenuation of the waves with their propagation distance, they do not play a significant role in motion on the plate surface. Furthermore, as soon as the first incident wave packet generated by the source separates at *tip A*, the portion travelling above the delamination slows down relative to the portion travelling below it. A detailed analysis of this behavior is given by the authors in [10] and can be explained by considering the acoustic impedances mismatch between zones 1, 2 and 3. In the same work [10] the authors give the reason why the $A_0$ modes are more suitable to detect delamination and disbonding and the way to use the method to localize them in both flat layered and sandwich plates.

## 2 DAMAGE LOCALIZATION IN A STIFFENED COMPOSITE PLATE

The damage identification technique has been applied to a stiffened composite panel. The panel is 3.8 mm thick with I shaped stringers 1.9 mm thick and 45.8 mm high with a pitch of 120.0 mm.

A finite element simulation of wave propagation in the intact and disbonded configuration has been carried out to analyze the effect of the damage on the waves path in the stringer-panel bonding region. All the simulations and experimental tests here reported refer to a five sine cycles excitation in a Hanning window with a central frequency of 60 kHz. As showed in Figure 2, the waves path is strongly affected by the presence of the stringers. When the stringer is perfectly bonded to the panel, the wave travelling from the bay adjacent to a stringer (zone 1) enters the stringer travelling through the web up to the flange (zone 2), and only a little part of the energy (i.e. waves) crosses the stringer travelling in the panel (zone 3). This is due to the acoustic impedance mismatch between zones 2 and 3, as explained in [10]. Furthermore, the presence of a disbonded region between the panel and the stringer modifies path of the wave that now travels mostly in the panel crossing the stringer below the disbonded region (from zone 1 to 3) when the stringer to plate bonding is lost after impact. Figures 2a and 2b show the wave paths in the defect free and disbonded configuration as obtained by the FE simulations.

Some preliminary tests have been carried out in the lab on the defect free configuration, i.e. stringer perfectly bonded to the skin, to evaluate how the propagation characteristics change when the wave encounters the stringer. In Figure 3 the stringer with two adjacent panel bays and the locations of three piezo patches are sketched. The PZT #1 in Figure 3 works as source and PZTs #7 and #9, placed on the opposite side respect to the stringer, work as receiver. The same behavior observed in the finite element simulations is found in the experiments.

From the waveforms reported in Figure 4 it is observed a substantial loss of amplitude of the wave travelling across the stringer (path 1-9) respect to the amplitude measured by the receiver 7 in the same bay path (1-7). In fact, with reference to the Figure 2a, the wave generated at the point 1 propagates to zone 1 and then is split into two propagation paths, to zone 2 and 3, respectively. As the thickness in zone 2 (stringer web) is lower than in zone 3 (panel and stringer base), most of the Ao wave energy will go up to stringer web instead of crossing the stringer to travel to zone 3

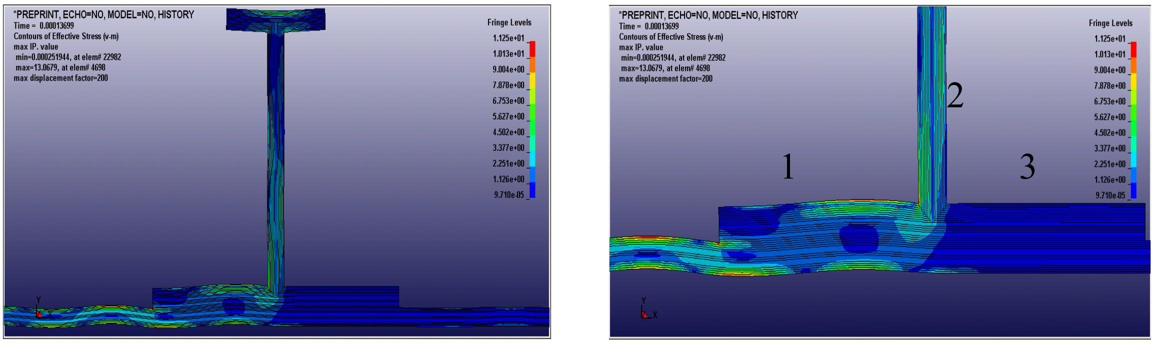


Figure 2a: FE simulation of the waves path in the damage free configuration of the stiffened panel (left) and a close-up (right).

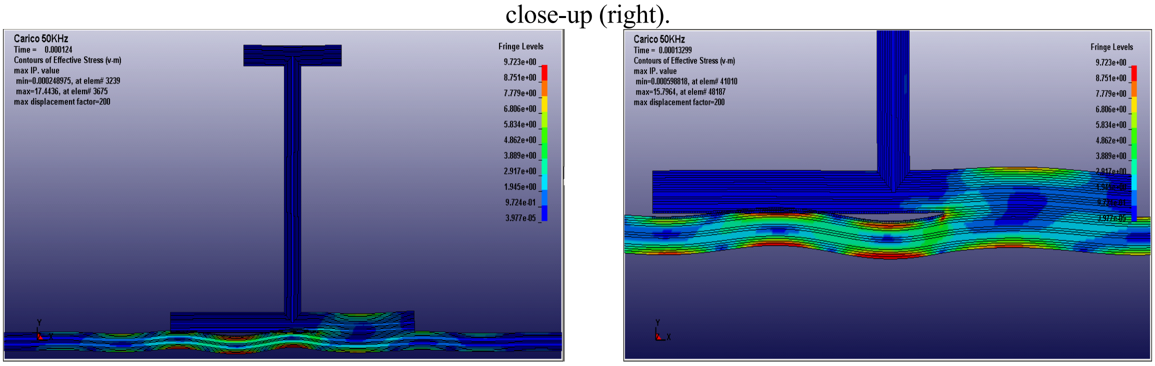

Figure 2b: FE simulation of the waves path in the disbonded configuration of the stiffened panel (left) and a close-up (right).

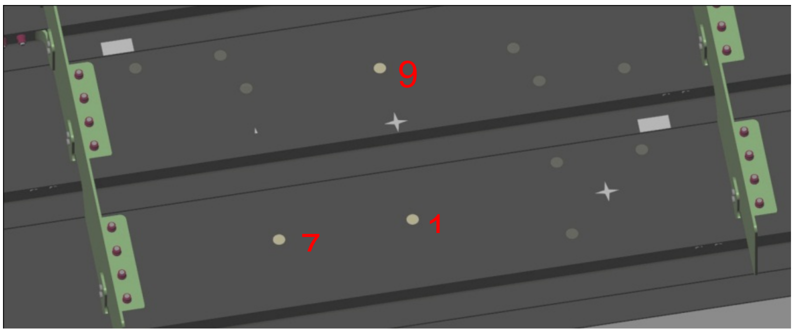


Figure 3: Experiments: amplitude modification of the guided waves due to the presence of the stringer

The stiffened panel has been then impacted with an impact energy providing a stringer-panel disbonding. Wave propagation tests have been conducted before and after the impact using an array of sources and receivers. In Figure 5 a sketch of the stiffened panel, with source and receiver PZTs and impact locations is reported. A picture of the panel with the PZTs bonded is also showed in Figure 5. Although multiple impact damages at different impact energies have been produced in the test article, in the present work we are focused on the impact location 5 (pointed out by a circle) for which a stringer disbonding of 40 mm x 80 mm has been achieved, as assessed by CScan tests (see Figire 5).

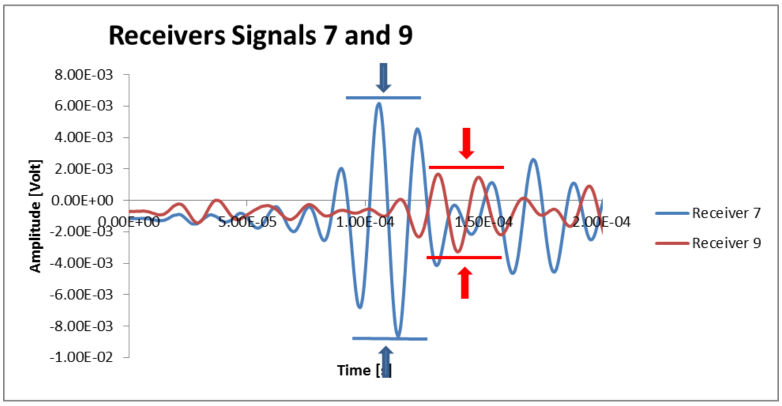


Figure 4: Experiments: amplitude modification of the guided waves due to the presence of the stringer

The amplitudes of the signals received from piezo 6’ when 7’ is generating (see Figure 6) is about 3 times higher in case of disbonding, as showed in Figure 5. Moreover the group velocity of the $A_0$ waves through the stringer region suffers a decrease of about 14% in the case of disbonding (see Table 1), due to the fact that the acoustic impedance is lower because of the reduced overall thickness in the disbonded region.

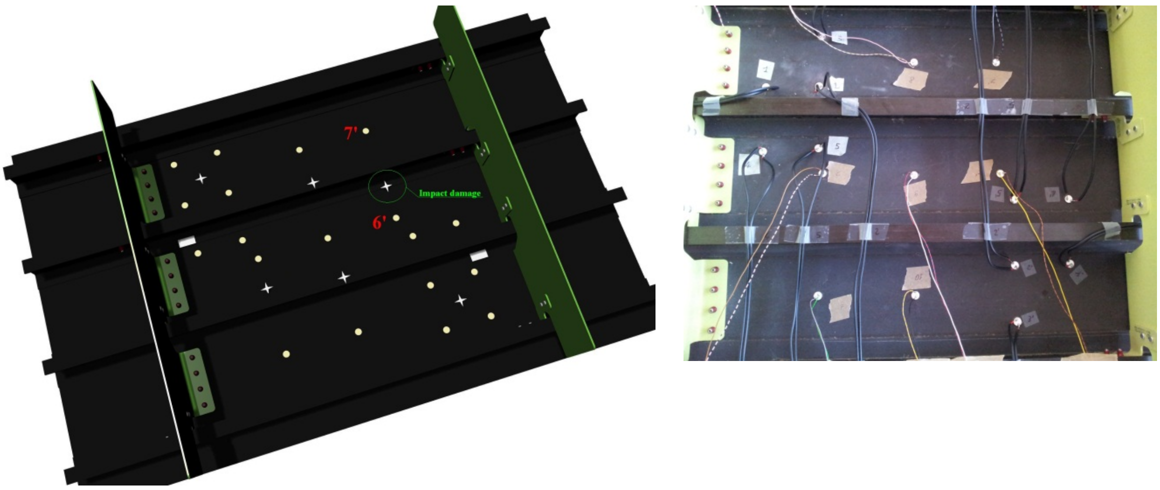


Figure 5: Top view of the stiffened plate with PZT (circles) and impact locations (stars), left. The disbonded region under investigation is the *5, PZT 6’ and 7’ are used to detect the disbonding. Experimental set-up, at right.

## CONCLUDING REMARKS

The first anti-symmetric mode of Lamb waves ($A_0$) is very effective in delamination and disbonding detection in layered plates. The interaction of guided waves $A_0$ modes with delamination or disbonding carries important information on the damage location. The Finite Element simulations carried out in the two dimensional model provide a good understanding of the interaction process. A good agreement between simulations and experimental results has been achieved. Using inexpensive, easy to install piezoelectric patches, it is possible to monitor even complex structures, such as composite stiffened panels, to detect delaminations produced by operation load or low velocity impact damage.

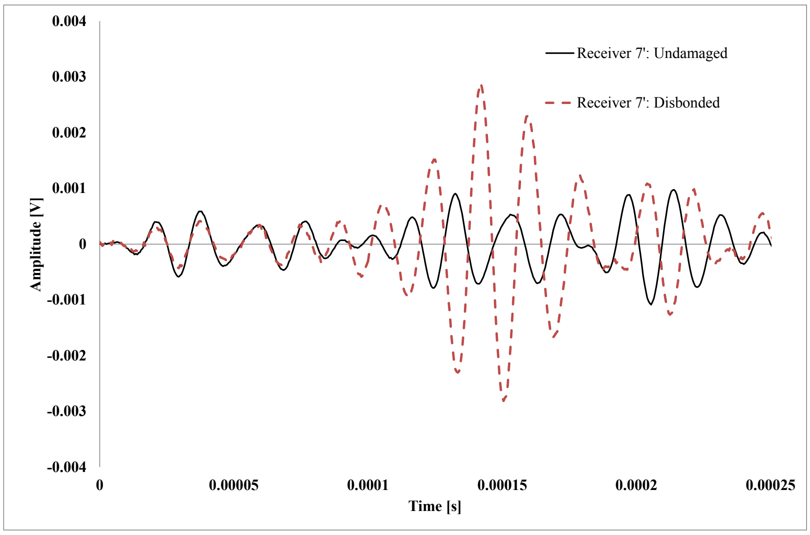


Figure 6: Influence of the stringer-panel disbonding on the $A_0$ waves travelling in the panel and transmitted across the stringer: source is in 6', receiver in 7' (ref. Fig. 4).

| | Intact | Damaged | Comparison |
|---|---|---|---|
| Path | v [m/s] | v [m/s] | Δv % |
| 6' –7' | 1604 | 1376 | 14.2 |
| 7'- 6' | 1596 | 1376 | 13.8 |

Table 1: Influence of disbonding on $A_0$ waves group velocity at 60 kHz.

## REFERENCES

[1] Kudva J.N., Grage M.J., Roberts M.M., "Aircraft structural health monitoring and other smart structures technologies — perspectives on development of smart aircraft", Proceedings of the 2nd International Work shop on Structural Health Monitoring, Stanford, September 1999, pp.122–132.
[2] Bar-Cohen Y, "Emerging NDE technologies and challenges at the beginning of the 3rd millennium – Part II NDT.net 2000; 5(2):1-10
[3] Mal A.K., Ricci F., Samajder H., Baid H. "NDE of composite structures using ultrasonic guided waves" Proc. SPIE 8695, Health Monitoring of Structural and Biological Systems 2013, 86950E (April 17, 2013);
[4] B. Lee, W. Staszewski, Modelling of Lamb waves for damage detection in metallic structures: Part I and II. Wave propagation, Smart Materials and Structures 12 (2003) 804-814 and 815-821.
[5] C. Ramadas, Krishnan Balasubramaniam, M. Joshi and C. V. Krishnamurthy, "Interaction of Lamb mode (A0) with Structural Discontinuity and Generation of ''Turning modes'' in a T-joint", 2011 Elsevier.
[6] Mal, A. K., and Lih, S.-S., "Elastodynamic Response of a Unidirectional Composite Laminate to Concentrated Surface Loads: Part I," J. Appl. Mech. 59, 878-886 (1992).
[7] Lih, S.-S., and Mal, A. K., "Elastodynamic Response of a Unidirectional Composite Laminate to Concentrated Surface Loads: Part II," J. Appl. Mech., 59, 887-892 (1992).
[8] Lih, S.-S., and Mal, A. K., "On the Accuracy of Approximate Plate Theories for Wave Field Calculations in Composite Laminates," Wave Motion 21, 17-34 (1995).
[9] Chang, Z. and Mal, A. K., "Wave Propagation in a Plate with Defects," Review of Progress in QNDE Vol. 17, 121-128 (1998).

[10] Ricci F., Monaco E., Baid H., and Mal A.K "Guided Waves in a Disbonded Honeycomb Composite Structure" Proc. Of 9th International Workshop on Structural Health Monitoring, Stanford University, CA, September 10-12 2013.
[11] S. Grondel, C. Paget, C. Delebarre, J. Assaad, K. Levin, Design of optimal configuration for generating A0 Lamb mode in a composite plate using piezoceramic transducers, Journal of the Acoustical Society of America, 112 (2002) 84-90.
[12] M. Bruneau, T. Scelo (translator and contributor), Fundamentals of Acoustics, ISTE, 2006.