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Application of laser Doppler vibrometry for ultrasonic velocity assessment in a composite panel with defect

L. Maio*, F. Ricci, V. Memmolo, E. Monaco, N.D. Boffa

University of Naples "Federico II", Department of Industrial Engineering – Aerospace Section, Via Claudio, 21, 80125 Naples, Italy

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ABSTRACT

The measurement and analysis of the velocity and other properties of guided waves are commonly carried out using a variety of techniques. Depending on devices employed in the experiments, the instrumentation limitations must be taken into account in order to ensure the accuracy of the measurements. In this paper, the characteristics of guided waves propagating in a quasi-isotropic composite with an embedded Teflon film, that can simulate the presence of a delamination, are studied. The guided waves are created by means of a piezoelectric transducer bonded to the surface of the laminate and the signals are acquired by a high precision laser Doppler vibrometer. A signal analysis methodology is adopted to estimate the group velocity of the propagating wave packet, first in the undamaged region of laminate and then in the region containing the simulated delamination. The measurement error is discussed and appropriate formulas are presented for uncertainty quantification in the velocity calculation.

1. Introduction

Ultrasonic guided waves (UGW) constitute a new interesting methodology in the field of Non-Destructive Evaluation (NDE) [1]. The use of UGW in solid media has been discussed for over 60 years; Worlton [2] was one of the first to recognize their potential in the structural inspection. They are mechanical stress waves that can propagate for long distances in thin-wall structures (thickness lower than wavelength of the propagating oscillation) and with very little amplitude loss when excited at low frequency [3–6]. UGW are useful to correlate the wave propagation anomalies in a structure with internal damage (in general, boundaries and other material or geometry discontinuities) to the structure itself [7]. For this reason, they are particularly suitable for Structural Health Monitoring (SHM) applications, where the objective is to provide, at every moment during the life of a structure, a diagnosis about the state of its different parts. Further information on ultrasonic guided waves can be found in many excellent textbooks [8–13].

Although their usefulness, it is necessary to emphasize that guided wave propagation behavior is much more complex than that of bulk waves; first of all, guided waves have dispersive characteristics (i.e., the wave velocity changes with frequency, modes, and plate thickness [14–16]); then, if the propagation occurs in a non-homogeneous material, for example in a composite laminate, the wave behavior is complicated by the medium heterogeneous nature, its inherent anisotropy and the multi-layered construction which lead to the wave mode velocity being macroscopically dependent on the laminate layup, the direction of wave propagation and interface conditions [17,18]. To overcome this difficulty, the use of approximate numerical methods [19,20], providing diverse solutions to time-transient Lamb wave response under certain conditions, is beneficial to understand the fundamental physical principles of guided wave propagation and to evaluate the propagation characteristics of guided waves in general cases. However, a successful numerical approach to a practical problem should be possibly supported by experimental tests.

From the experimental side, one of the devices commonly used to generate and detect ultrasonic waves in structural materials (typically between 50 kHz to 300 kHz) is the piezoelectric transducer based on lead zirconate titanate (known by the acronym PZT) that can be easily surface-bonded on a host structure. PZTs are particularly attractive for SHM systems because of their sensitivity, small size, low cost, non-intrusive nature and light weight characteristic. However, there are some drawbacks associated with the piezoelectric transducers. First of all, they require a coupling medium in order to efficiently transmit acoustic energy into a structure. This coupling layer modifies the amplitude of a wave produced by a transducer every time it is removed and re-attached. Thus, the entire test becomes unrepeatable from specimen to specimen (or even test to test). This disadvantage can be

* Corresponding author.
E-mail address: leandro.maio@unina.it (L. Maio).
URL: http://www.asm.unina.it (L. Maio).

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critical in some applications, especially for those involving amplitude measurements [21]. Secondly, the PZT has a finite size. In general the size of a transducer cannot be neglected if the size itself is comparable to any of the length parameters of the problem (such as thickness, propagation distance, wavelength, etc.). In such cases, diffraction or a spreading of a wave beam must be taken into account. Thirdly, when the geometry of the structure under investigation is complex and a very large number of measurement points is needed, the discrete point-by-point approach performed by the use of PZT transducers becomes highly time-consuming. Finally, the last major drawback of a conventional piezoelectric transducer is that it still requires electrical wiring for power and data transmission just like many other conventional sensors, and the wiring of an array of sensor can be difficult to realize. Conventional wires are also susceptible to electromagnetic interference, corrosion, noise and may cause signal attenuation over a long sensing range.

Another approach to develop and detect ultrasonic waves is the laser-ultrasonic technique [22]. When it is used for the wave generation, the electromagnetic radiation from a short laser beam is pulsed onto the surface of a structure, causing localized heating. The heated region undergoes thermal expansion, and ultrasonic waves are produced. However, this excitation type may cause ablation; furthermore, it is difficult to control the frequency and waveform of the laser excitation. For ultrasonic sensing, the commonly used detectors are laser interferometers [23] or laser Doppler vibrometers (LDV) [24]. These sensing devices are often bulky and expensive, have much lower sensitivity compared to PZTs, and typically measure only out-of-plane displacements or velocities [22], unless used in 3D configuration; therefore, they are commonly considered for laboratory set-up. The laser technique for wireless measurement of guided waves is more effective when compared to transducers in terms of frequency bandwidth and fidelity (frequency-unbiased in the range of interest). In contrast to other sensor system, it offers an ideal, non-contact solution, that can be easily and spatially distributed since a laser beam can be focused to a point by an optical lens; therefore, any size-effect is eliminated.

Traditionally the LDV is employed as a single-point sensor measuring vibrations on a grid of points marked on the structure; it steps on each of them manually or by the mean of a scanning system, made up of two mirrors having orthogonal axes, which rapidly and precisely deflect the laser beam towards the pre-selected measurement points. The assembly of the two systems (laser sensor and scanning device) constitutes the so-called scanning laser Doppler vibrometer (SLDV).

Nowadays, the SLDV is used in many applications as an alternative to conventional transducers (i.e. modal analysis [25–30], dynamic testing [31,32], noise detection [33], quality control [34,35] and damage identification [36,37]).

This paper deals with the application of scanning laser Doppler vibrometry for ultrasonic velocity assessment in a composite laminated structure with an artificial defect embedded into lamination sequence. The knowledge of velocity of a wave mode is very useful when time signals are used in guided wave based structural health monitoring; its accurate determination is the key to locate the sources of acoustic emission [38] or for the identification of waves reflected by a damage [39]; therefore, it is important to understand how measurement error affects the data analysis, and consequently the scientific conclusions.

For the purpose, a single PZT is utilized for antisymmetric guided wave generation in the composite plate and the corresponding structural response is measured at many points along single lines in different directions and regions using the SLDV. The main goal of this work is to deeply investigate both the influence of various acquisition parameters on the correct wave signal acquisition and the corresponding induced measurement errors that can affect the velocity estimation of a wave packet in three specific regions: far from the artificial defect, close to the defect and in correspondence of its location. The analysis of variation of the propagation velocity when waves passes through these three regions permits theoretically to identify and locate the defect reliably but an accurate choice of the acquisition parameters is fundamental in order to avoid wrong interpretations of experimental results; such investigation represents the main achievement of this study as demonstrated in the following paragraphs.

2. Approach to the study of group velocity behavior

The guided waves require a structural boundary for propagation, differently form bulk waves which are not affected by boundary presence [16]. Examples of guided waves are Rayleigh surface waves, Stonely and Lamb waves. The latter are the focus of this work.

The Lamb waves are widely acknowledged among the most promising tools for quantitative identification of damages in composite structures and they are commonly used in NDT (Non-Destructive Testing). These elastic waves propagate in structures with thickness smaller than the wavelength; therefore, they can be easily generated in plate-like body.

A finite body can support an infinite number of different guided wave modes. These modes exist for a specific plate thickness and frequency and they can be identified thanks to their respective velocities. Below the cutoff frequencies of the higher wave modes only three fundamental modes can exist; the first antisymmetric mode A_0, the first symmetric mode S_0, and the shear mode SH_0. Generally, A_0 and S_0 modes are the most employed in damage detection techniques; however, the antisymmetric mode (representing physically a flexural wave), is more suitable, compared with the symmetric one, for small damage detection, due to its shorter wavelength and dispersion characteristics at low frequencies [18,40].

Guided waves can be excited using a piezoelectric transducer bonded to the surface of the plate. The selection of shape and carrier frequency of the excitation signal is very important since the guided waves are dispersive and this means that, after travelling a long distance, wave packets of different frequencies will separate from each other and distort the signal making the analysis much more complex. To minimize these effects, a narrowband signal is preferred; a sinusoidal tone-burst excitation (which is a wave train consisting of several cycles at the same frequency) is used due to its reduced bandwidth [41,42]. The number of cycles is another important parameter having direct influence on the signal frequency content: the effective bandwidth of the signal is inversely proportional to the signal duration. The 4.5 sine cycles filtered with a Hanning window (which reduces spectral leakage) represent a good choice as excitation signal in order to obtain a narrow-band bell curve in the frequency domain with the energy concentrated around the desired center frequency.

The test article employed in this study is a 600 × 600 × 1.6 mm CFRP plate consisting of 8 unidirectional plies stacked with a symmetric and balanced lay-up ($[45/-45/0/90]_s$). The mechanical properties of the composite material are listed in Table 1. The panel is manufactured through a handy layup process using pre-preg material. A circular film of polytetrafluoroethylene (PTFE), 15 mm in diameter, simulating a defect, is inserted during the manufacturing at the second interface (i.e. between the 2nd and 3rd ply). A schematic sectional view showing the laminated panel is given in Fig. 1.

The object under investigation is inspected with an ultrasonic linear

Table 1
Properties of CFRP material.

Mechanical Property	E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	G_{12} [GPa]	G_{13} [GPa]	G_{23} [GPa]	ν_{12}	ν_{13}	ν_{23}	ρ [kg/m^3]
	175	6.90	6.90	4.18	4.18	2.35	0.25	0.25	0.46	1520