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LAMB WAVES IN MULTILAYERED ANISOTROPIC MEDIA

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The use of composite materials in various industrial fields is becoming increasingly common. Composite materials, particularly laminar composites, can perform better than metallic materials in many situations. One of the reasons is their high strength-to-weight ratio. Laminated composites typically have a large number of layers, with each layer characterized by an ordered fiber structure in one or more directions. The in-plane strength of laminated composites is enhanced by the presence of fibers, but the strength between layers is relatively weak. Therefore, delamination between adjacent layers is the most common type of defects occurring in a composite plate [1].

Lamb wave testing is one of the most promising delamination detection methods due to its high efficiency and accuracy. Lamb waves are guided ultrasonic waves that can travel long distances in plate or tubular structures with relatively low attenuation. This type of testing is multi-scale, i.e. suitable for both local volumes of composites and large planes of laminate layers.

The interaction of Lamb waves with delamination inside the composites as a final result leads to the separation of the fixed wave into transmitted and reflected structures. In turn, mode conversion is observed at the edges of the sample, followed by the generation of new modes. Experiments on fixing delamination can be divided into two groups. In the first group, the observation of reflected waves is implemented in the pulse-echo configuration. The second group is characterized by the implementation of constant monitoring of changes that occur with transmitted waves in the tone capture configuration. It should be noted that in the pulse-echo configuration, reflected waves are generated when the Lamb wave enters and exits the bundle, and the reflection at the output is much larger [2].

Changing the reflected and transmitted waves with the delamination length made it possible to implement the delamination localization method. In particular, delamination localization can be based on an estimate travel time of the reflected wave [3, 4]. Reflection cannot be observed under symmetric excitation when delamination exists in the mid-plane of the laminated composite. In a pitch-to-capture strain testing configuration, new wave packets may be observed due to mode conversion during delamination. Experimental results indicate that delamination can cause a delay in the arrival time of the transmitted wave. Additionally, one of the distinguishing characteristics of Lamb waves is that they propagate independently and at different speeds in two layers separated by delamination, and the length of the delamination can be determined by measuring the difference in arrival times of the two wave packets.

The dispersive nature of Lamb waves means that their group and phase velocities vary with frequency. As a result of dispersion, the received signal will have a smaller amplitude. In addition, this same signal is characterized by a long lifetime in comparison with the exciting signal. The result of these trends may be a decrease in the resolution of recording deformations in composite layers using Lamb waves. These facts are the reason why broadband excitation can be considered as an unfavorable fact. Consequently, most studies on condition monitoring of laminated composites are carried out using a window signal. The windowed signal is frequency modulated to reduce the excitation bandwidth and effectively minimize the dispersion effect.

As a rule, the beginning of testing is characterized by a lack of information about the optimal scanning frequency. Therefore, the preferred procedure is to record signals at different excitation frequencies. However, it should be noted that implementing narrowband excitation tests individually is time consuming. A common method nowadays is to use a chirped signal for excitation, which allows, using a deconvolution mechanism, to defragment multiple narrowband responses [5]. The extracted narrowband Lamb test responses are similar to the excitatory tone pulse responses.

Parameters that influence wave interactions in multilayer composites include the properties of the composite layers, sample geometry, directions of Lamb wave propagation, frequency of reflected waves, and interfacial conditions. In this work, we investigated the case when the lengths of the emitted waves significantly exceeded the dimensions of the components of the composites. In particular, the diameters of the fibers and the distance between them were significantly smaller than the wavelengths of signal emission. Each laminar composite slab was examined as an equivalent homogeneous and isotropic material with an axis of symmetry parallel to the fibers. The core of the analytical study was the wavelet transform of the response signal. The results of the wavelet transform made it possible to construct a map of the deformation field of a laminar composite sample.

Symmetric laminar composites were correlated with symmetric and antisymmetric Lamb wave modes. For symmetric modes, the notation qSn was used, with the dominant component of the polarization vector located along the propagation direction. Modes with a polarization vector that was predominantly parallel to the plate plane were characterized by a quasi-horizontal shear (qSH2n). For antisymmetric types of wave modes, quasi-bending (qAn) and quasi-horizontal shears (qSH2n-1) are generated.

The wave motion was considered as a superposition of plane harmonic waves due to the fact that Lamb waves propagate along the plane of the plate with boundaries free from cohesive forces, but are standing waves in the direction perpendicular to the unloaded plane of the sample.

Dispersion curves of Lamb waves in layered composites were obtained for five symmetric and five antisymmetric wave modes. All Lamb waves, with the exception of the fundamental modes (A0, S0 and SH0), have cutoff frequencies. Note that the interaction of Lamb waves with delamination has been most studied in the low-frequency range, where only fundamental modes exist. SH0 and S0 modes have low dispersion in the low-frequency range, below the frequency xh/cT = 0.5.

The calculation results showed that different frequency components inside the wave packet propagate at almost the same speed. This fact is the reason why the wave packet maintains its shape as it moves. Apart from this desirable feature, lower attenuation compared to waves for the A0 wave mode and high sensitivity to delamination are two other reasons that have increased interest in the use of symmetric modes as diagnostic waves.

The amplitude of the symmetric mode S0 is significantly smaller in magnitude compared to the amplitude of the A0 mode if both modes are excited simultaneously. As a result, the mode of using the A0 wave mode is preferable when diagnosing damage to the structure of composites.

Analysis of dispersion curves showed that mode A0 provides higher resolution than modes S0 and SH0. The reason for this is the fact that the wavelength of the A0 mode is always shorter than that of the S0 mode, especially in the low frequency range. In the higher frequency range, Lamb wave propagation in a relatively thick symmetrical corner laminate exhibits rather complex behavior.

The group velocity for the SH0 and S0 modes has a fairly high level of dispersion. In addition, targeted analysis showed that the symmetric mode dispersion in the quasi-isotropic laminate is significantly stronger. On the other hand, the dispersion of the antisymmetric wave mode A0 in the laminate is weaker beyond the frequency xh/cT = 1.

The results of calculations of group velocity dispersion surfaces for wave modes in the laminar composites used make it possible to represent the polynomial dependence in matrix form.

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