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ATTENUATION OF LAMB GUIDED WAVE IN LAMINAR COMPOSITES

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Abstract. *In this study, the Rayleigh attenuation model was used to calculate the Lamb mode attenuation constant in terms of the damping coefficient, group velocity, and excitation center frequency. The attenuation of Lamb waves was modeled using the finite element method. It was found that the numerical simulation of Lamb wave attenuation using the Lamb mode attenuation constants was in good agreement with the predicted attenuation. The Lamb mode attenuation constants calculated using the damping coefficient were used to model the Lamb mode attenuation in quasi-isotropic laminates. The numerical simulation of the amplitude change was found to be in good agreement with the experimental measurements. The calculations were performed based on the basic technique, which involves passing a Lamb echo pulse through the volume of a laminar composite to measure the attenuation coefficient. The attenuation coefficient was determined based on numerical data comparing two amplitudes of a certain mode obtained at two corresponding distances. Detection of acoustic nonlinearity in constant thickness composite samples at a fixed input fundamental frequency was possible using the characteristic wave mode. The functional dependence for the nonlinear parameter of Lamb waves was analyzed. It was found that this parameter is determined as a function of frequency, mode type, material properties and waveguide geometry.*

Key words: *Rayleigh attenuation model, laminated composites, Lamb waves, attenuation coefficient, group delay method.*

Introduction.

A large number of experimental and analytical studies on the propagation characteristics of Lamb pulses in the volume of composites lead to the conclusion that there are two main mechanisms of amplitude attenuation, which are "material attenuation or damping" and "wave packet propagation" corresponding to the wave dispersion effect. Since the guided wave modes in this study are selected in the non-dispersive frequency range, it is assumed that the amplitude decay is mainly affected by the attenuation. Attenuation is an important characteristic of the propagation of the Lamb guided wave [1]. The attenuation effect is equivalent to the decrease in signal strength after the wave travels a certain distance. The attenuation of the wave is determined by the attenuation coefficient. The fundamental symmetric mode (S0) has less attenuation than the fundamental antisymmetric mode (A0) when propagating through a viscoelastic material such as composites [2]. Antisymmetric modes propagate with minimal attenuation in structures having a metal-like lattice. However, in composites, the attenuation of antisymmetric modes is much higher than that of symmetric modes. There are two causes of Lamb wave attenuation: geometry and material. Attenuation due to geometry occurs when a Lamb wave propagates through damaged areas and/or collides with the edges of a plate. In this type of attenuation, no energy is dissipated. Lamb wave attenuation due to material is inherently present in a propagating medium such as composites. In general, attenuation is present when a guided wave propagates with a significant volume concentration of defect structures. The study of damping characteristics in the work requires the use of a mathematical model for the dynamic response of the structure, proportional to the stiffness and density of the material (Rayleigh damping). An important part of the Rayleigh damping is the determination of the proportionality constants of the mass and stiffness, respectively. These two parameters must be used as input data in the numerical model to include the Rayleigh damping in the vibration analysis. In this paper, the Rayleigh damping model is used to study the attenuation of Lamb waves. The proportionality constants are expressed through the damping coefficient, the group velocity and the central frequency of the excitation.

Surface impedance methodology.

A typical experimental technique using Lamb pulse echo to measure the attenuation coefficient is to compare two amplitudes of a particular mode captured at two corresponding travel distances on surface. We denote the attenuation value as α. The magnitude of the attenuation uniquely determines the decrease in the wave amplitude depending on the frequency and mode. Therefore, the following relationship is true

$$\ln\frac{A_{x1}}{A_{x2}} = \alpha\left(x_2 - x_1\right), \quad (1)$$

where A_{x1} and A_{x2} are the amplitudes of the wave mode signal;

x_1 and x_2 are the signal travel distances.

The nonlinear parameter of the second harmonic of the Lamb wave satisfies the following relation

$$\beta = \frac{8A_2}{k^2 A_1^2 x} f_x, \tag{2}$$

where k is the wavenumber of the Lamb wave;

f_x is the special function of the Lamb wave nonlinear parameter β.

This function can be expressed in trigonometric form

$$f = \frac{\cos^2(ph)}{\cosh(2ph)}\left[1 - \frac{(k^2 + q^2)}{2k^2}\right], \tag{3}$$

where h is the thickness of the waveguide; $p = (k^2 - l^2)^{0.5}$; $q = (k^2 - t^2)^{0.5}$.

The functional dependence for the nonlinear parameter of Lamb waves leads to the unambiguous conclusion that this parameter is determined as a function of frequency, mode type, material properties and waveguide geometry. The characteristic mode of the wave is chosen to detect acoustic nonlinearity in samples with constant thickness at a fixed input fundamental frequency. When studying the acoustic nonlinearity S1 at fixed frequencies, the influence of the characteristic function can be neglected.

Theoretical analysis has shown that the normalized amplitude of the second harmonic can be represented as the ratio of the amplitude of the second harmonic divided by the square of the amplitude of the fundamental wave (A_2/A_1^2). In terms of graphical illustration, such a feature corresponds to the slope of the line relating the actual acoustic nonlinear parameter β to the propagation distance x for a fixed wave number k and nonlinearity function f. In this case, the normalized amplitude of the second harmonic can be written as

$$\overline{\beta} = \frac{A_2}{A_1^2} \alpha\beta x. \tag{4}$$

The normalized amplitude of the second harmonic increases with the propagation distance due to the presence of a cumulative effect. The increase is observed up to a certain point, when the material attenuation becomes dominant. Checking for this cumulative effect in measurements is important. Namely, the presence of the effect ensures that the measurements from the samples are not due to the uncertainty of the measuring system, but to the nonlinearity caused by the damage.

Summary and conclusions.

The phase matching of the wave mode pair (S1, S2) to generate the cumulative second harmonic wave avoids the dispersive and multimode nature of the Lamb ultrasonic wave propagation. The group delay method is used to effectively separate a large number of wave packet modes. The basis of this method is the difference in group velocities among the different Lamb modes. The Rayleigh damping model allowed us to obtain the damping constants of the Lamb mode. The amplitude variations of the Ao and So modes obtained from the numerical simulations performed on the cross-laminated and quasi-isotropic laminates showed good agreement with the actual variation/damping. Overall, it is concluded that the numerical methods that use the Rayleigh damping for vibration analysis can be used to realize the damping of the Lamb wave due to propagation in laminar composites.

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