ULTRASONIC NONDESTRUCTIVE EVALUATION OF CRACKED COMPOSITE LAMINATES

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INTRODUCTION

The use of guided waves in the ultrasonic nondestructive evaluation of structural components, e.g., bonded plates and composite laminates, has received considerable attention in recent years. Highly accurate and efficient experimental techniques have been developed to generate, record and analyze these waves in laboratory specimens, leading to an improved capability in flaw detection and material characterization in a variety of materials [1-4]. A convenient method to generate guided waves in a plate or laminate is the so-called leaky Lamb wave (LLW) technique. It has been demonstrated in several recent papers [5-7] that phase velocity and amplitude of guided waves composite laminates can be determined very accurately in a broad range of frequencies and velocities by the LLW technique.

The main objective of the research presented here is to simulate the LLW experiment in an effort to develop a nondestructive method for the material characterization and damage evaluation of composite laminates. In order to validate the theoretical model of composite, the reflected field from a composite laminate immersed in water and obliquely insonified by an acoustic beam is calculated and compared with laboratory data. The specimens can be either unidirectional or multi-orientation undamaged laminates of arbitrary thickness. Both time harmonic and transient waves are considered.

After model validation, the phase velocities of free and leaky guided waves in both unidirectional and multi-orientation laminated composites are studied and compared with LLW data to determine their stiffness constants. Finally, the wave behavior in a unidirectional composite containing a delamination and in a multi-orientation laminate permeated by a number of small transverse cracks. The depth of the delamination is determined from the amplitude spectra of the reflection coefficients. A systematic inversion scheme is used to determine the stiffness degradation of damaged laminates containing transverse matrix cracks.
THEORY

Fiber-reinforced composite materials are heterogeneous and composed of at least two phases. A large number of parallel, cylindrical fibers embedded in the matrix introduces an axial symmetry in the effective elastic property of the material. It is reasonable to assume that the material is elastically transversely isotropic and homogeneous in its overall static behavior. The laminates are assumed to be uniform transversely isotropic plates with symmetry axis parallel to the surfaces of the plates. The resin layers between two adjacent laminae can be modeled by isotropic viscoelastic layers, but they are ignored in the calculations here.

We consider a fiber-reinforced composite plate immersed in water and insonified by a plane harmonic acoustic wave (Fig. 1). We wish to calculate the reflected field as a function of frequency and angle of incidence. The detailed formulation is described in [8], and will not be repeated here.

The basic idea behind the inversion is data fitting to theoretical models. A major difficulty in inversion is that it requires the solution of a system of nonlinear equations, resulting in non-uniqueness [9]. In this study, a least squares method for the nonlinear, implicit model presented by Britt and Luecke [10] is applied to estimate the material properties of damaged composite laminates.

The minima in the amplitude spectra of the reflection coefficient $\Delta$ correspond to the modal frequencies of dispersive guided waves in the laminate. The reflection coefficients are complex-valued functions of frequency, laminate thickness as well as the material properties of the composite and the surrounding fluid. Let $\Delta$ be expressed as

$$\Delta = \Delta_R + i\Delta_I$$

(1)

where $\Delta_R$ is a smooth function. The modal frequencies of both free and leaky guided waves are almost identical in a broad frequency range. The real part of (1) is related to the dispersive guided waves and the imaginary part is contributed by the influence of water loading. $\Delta_I$ is approximately zero at the modal frequencies because of small influence of water loading, and dispersive guided waves are excited at the frequencies where $\Delta_R$ vanishes. The dispersive guided waves satisfy a system of equations that corresponds to the phase velocity or the angle of incidence of the form

$$\Delta_R - G(\mathbf{f}, \mathbf{v}, \mathbf{C}) = 0$$

(2)

where $\mathbf{f}$ is the vector of modal frequencies, $\mathbf{v}$ is the vector of phase velocities and $\mathbf{C}$ is the vector of stiffness constants, $C_{ij}$.

Fig.1 Schematic diagram of the LLW experiment