Quantitative Estimation of Crack Position and Dimension in a Plate Using Lamb Waves: Numerical Simulation

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Quantitative assessment of the crack position and dimension in metallic structures is critical to nondestructive testing and evaluation. Finite-difference time-domain method was used to simulate the propagation of Lamb waves in a plate and its interaction with cracks. The corresponding reflection and transmission coefficients and power spectral densities were used as the training data for direct search and an artificial neural network model. The estimation accuracy was compared with each other at varied detection thresholds. In addition, detecting multiple cracks was also possible by considering each crack individually, if the echoes from each crack can be separated in the time domain.

1. INTRODUCTION

The occurrence and development of fatigue crack as a foremost damage source is critical in metallic structures. Various methods have been developed for inspection, such as visual inspection, radiography, eddy current testing, optical, and ultrasonic method.1 However, these processes are quite time-consuming, expensive, and require the structural system to be idle. Therefore, a continuous, in-service structure health monitoring (SHM) system is highly desired. SHM could be realized by numerical procedure, such as a boundary element code implemented in the framework of piezoelectricity for debonding and delamination cracks2 and passively sensing any perturbations caused by possible hidden damage using advanced signal processing.3,4 Lamb waves, a type of guided elastic waves that propagate with little attenuation over long distances in thin plate-like structures with free surfaces, can offer a convenient method for quick and continuous inspections. During the wave propagation, the particles move either symmetric or anti-symmetric to the mid-plane of the plate. With appropriate mode selection, Lamb waves carry characteristics that are correlated with the location and severity of a defect over a relatively long propagation distance (i.e., global inspection capability) even in materials with high attenuation ratios. Lamb waves have subsequently been successfully employed to detect and monitor fatigue cracks in metallic structures or around through holes over a broad area using only a few transducers.5 Complete information about a crack including its location, size, and classification is an important issue, which makes this technique more useful, allowing for predictions of the remaining lifetime of the structure and changing the loading conditions, rather than a defect screening method only. However, as an inverse problem, it is difficult to quantitatively determine the properties of damage directly from the characteristics of Lamb wave propagation (i.e., the reflected and transmitted waves from the crack).

Computer simulation and visualization of Lamb waves are effective tools to clarify such complex ultrasonic wave motions. General-purpose computational approaches, such as the finite difference method (FDM), finite element method (FEM), and boundary element method (BEM), are widely used for wave propagation, but computational time and memory become fatal problems in a large structure. For good convergence, fine spatial discretization is required in FEM since the element size should be at most one tenth of the smallest ultrasonic wavelength. A purely time-domain FEM can be combined with 2-D Fourier transform and normal mode expansion for the sake of computation cost, which is called global-local FEM technique.6,7 The BEM has advantages in wave scattering problems, such as reduction of dimensionality, high computational efficiency and less storage, and easy management of unbounded domains.8 In homogenous media, FDTD is similar to the elastodynamic finite integration technique (EFIT), but the latter has a relative simplicity and great flexibility and effectiveness for heterogenous media with even millions of grid cells tackled on an ordinary PC within reasonable computing time.9 Furthermore, EFIT also allows for the general nonlinear expression for the strain tensor and a nonlinear version of the constitutive equation.

To quantitatively assess the crack sizes, the direct approach is to first find the relationship between crack dimensions and the reflection/transmission coefficients, and then to search for the best match using the measured characteristics of Lamb waves.10 The artificial neural network (ANN) technique is a promising and robust tool for a nonlinear inverse problem with