MODELING AND EXPERIMENTS OF REFLECTION BASED NONLINEAR ULTRASONIC INSPECTIONS OF ADHESIVE BONDS

Do-Kyung Pyun[1], Lucas W. Koester[2], Daniel J. Barnard[2], Leonard J. Bond[1], [1]Department of Aerospace Engineering, Iowa State University, Ames, IA, [2]Center for Nondestructive Evaluation, Ames, IA

Adhesive bonds are used extensively to join components of like or dissimilar materials in the aerospace and automotive industries due to the advantages of lower stress concentration and improved fatigue load behavior. With the extensive use of adhesive bonds, there is a need of inspection techniques to determine the bond states. Nondestructive evaluation (NDE) techniques based on linear ultrasound are effective to detect disbond states. However, there are several limitations in the linear-based ultrasonic NDE techniques, when they are used for the evaluation of weak bond states and kissing bond. It is difficult to detect these bonds because the received ultrasonic waves passing through weak bonds or kissing bonds are distorted, which makes ultrasonic techniques using linear characteristics improper. To evaluate these bonds, nonlinear ultrasonic methods can be applied by examining the acoustic nonlinear parameter (ANP) [1]. The nonlinear ultrasonic methods measure both the amplitudes of fundamental and higher harmonic components. Conventional nonlinear methods are based on transmission approaches that are not applicable in many scenarios due to limited access to both sides of a component [2]. For this reason, one-sided methods are necessary, and a number of researchers have developed these nonlinear techniques including wave mixing techniques and pulse echo methods. Ju et al. showed that a two-wave mixing technique can be much more sensitive than linear reflection techniques in determining the effects of thermal aging on adhesive joints [3]. Also, Jeong et al. showed that fluid ANP may be determined for immersion inspections after corrections for beam diffraction and attenuation based on a pulse echo method [4].

In this study, analytical and numerical techniques to investigate reflection based nonlinear ultrasound on adhesive bonds are the focus of this work. Analytical formulations consider perfect bonded interfaces and the nonlinear effect of materials by considering second- and third- order modulus in Hooke's law as below.

$$\sigma = E\varepsilon + M\frac{\partial \varepsilon}{\partial x} \tag{1}$$

Where E is the second order modulus and M is the third order modulus.

In addition, the 1D Westervelt equation was applied to the commercial numerical tool, COMSOL Multiphysics, to inspect nonlinear interaction between ultrasonic waves and materials.

$$\frac{1}{\rho c^2}\frac{\partial^2 p}{\partial t^2} - \nabla\left(\frac{1}{\rho}\left(\nabla \mathrm{p} + \frac{\delta}{\rho c^2}\frac{\partial(\nabla \mathrm{p})}{\partial t}\right)\right) = \frac{\beta}{\rho^2 c^4}\frac{\partial^2 p^2}{\partial t^2} \tag{2}$$

Where p is the acoustic pressure, ρ is the density, c is the sound speed, δ is the acoustic diffusivity, and β is the acoustic nonlinearity parameter.

The nonlinear reflection coefficients of analytical and numerical techniques were compared with each other according to the range of frequencies and source amplitudes, and then compared with linear reflection coefficient. Furthermore, the tendencies of analytical and numerical reflection coefficients were verified by experimental results.

The results showed that the suggested analytical method of nonlinear reflection coefficient has a good agreement with numerical and experimental results. Also, there are several influence factors to the nonlinear reflection coefficient, such as frequency and source amplitude. Based on the results, it is possible to analyze more accurately adhesive bonds.

[1] Nagy, P. B., McGowan, P., and Adler, L., "Acoustic nonlinearities in adhesive joints," In Review of progress in quantitative nondestructive evaluation, pp. 1685-1692., 1990.

[2] G. Shui, X. Song, J. Xi, and Y.-S. Wang, "Experimental Characterization of Impact Fatigue Damage in an Adhesive Bonding Using the Second Harmonics," J. Nondestruct. Eval., vol. 36, no. 2, pp. 1–12, Mar. 2017.

[3] T. Ju, J. D. Achenbach, L. J. Jacobs, and J. Qu, "Nondestructive evaluation of thermal aging of adhesive joints

by using a nonlinear wave mixing technique," NDT E Int., vol. 103, pp. 62–67, 2019.

[4] H. Jeong, S. Cho, S. Zhang, and X. Li, "Acoustic nonlinearity parameter measurements in a pulse-echo setup with the stress-free reflection boundary," J. Acoust. Soc. Am., vol. 143, no. 4, pp. EL237–EL242, Apr. 2018.