PARAMETRIC ANGLE BEAM ULTRASONIC SPECTROSCOPY FOR THE EVALUATION OF ADHESIVE BONDS

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Abstract

We describe an experimental method incorporating high frequency angle beam pulsed ultrasonic measurements during low frequency vibrations of bonded structures. The parametric/nonlinear mixing between high and low frequencies is used for degraded bond identification. It is demonstrated that the effect of environmental degradation of adhesive bonds can be detected by this method: good quality (undamaged) bonds exhibit small dependence of their ultrasonic signatures on the overlay of low frequency vibration loads; however, environmentally degraded or imperfect bonds exhibit strong modulation of the spectrum minima of the ultrasonic signal reflected from the bond. The results are interpreted using a model for normal and oblique wave interaction with two nonlinear interfaces separated by an adhesive layer under quasi-static stress modulation.

Introduction

Environmental degradation of adhesive bonds of composite or metallic structures affects predominantly the adhesive/adherent interface by degrading molecular bonds between the adhesive and the substrate. The spectroscopic technique [1] is a valuable tool in characterization of adhesive bonds. Angle beam ultrasonic spectroscopy at normal and oblique incidence [2] can be used to determine adhesive bonding layer properties and degradation. To determine the optimal experimental conditions and to relate ultrasonic signature to joint quality the spring model of the interface [3, 4] between adhesive and substrates has been used. When the normal and shear spring stiffnesses are infinitely large, the interfacial bond is perfect; when the shear stiffness is infinitesimally small, the interfacial bond has no resistance to shear stress, i.e. it degenerates into an ideal slip bond (total disbond). Thus interfacial spring stiffness can be used as a quantitative parameter to describe the extent of interface damage in the linear ultrasonic method. Using this model we have evaluated critical parameters used in angle-beam spectroscopic inspection techniques, such as angle of incidence, selection of transducer frequency and position of spectral minima. In this way the properties of the bond line are reconstructed from the experimental data.

In this paper we report an integrated (linear and non-linear) ultrasonic method for quantitative characterization of bond integrity. The identification of the imperfect adhesive bond is enhanced by adding low frequency dynamic compression/tension vibrations at the bonded interface. It is shown that a good quality (undamaged) bond does not exhibit ultrasonic signature dependence on the low frequency vibration load; however, environmentally degraded or imperfect bonds exhibit shift of the resonance frequency of the reflected ultrasonic signal with load. Thus parametric/nonlinear mixing between reflected high frequency ultrasonic pulse and low frequency dynamic vibration is characteristic of an imperfect bond.

Method concept

To enhance adhesive bond characterization we combine linear and nonlinear methods by incorporating pulse echo linear spectroscopy with parametric low frequency pulse/frequency modulation. In the linear approach, we use obliquely and normally incident ultrasonic beam spectroscopy. The two angle measurements allow decoupling of elastic moduli and thickness of the interfacial layer. To do this we have developed a dual beam scanning approach. At each point of the scan, the normal and angle beam time domain signals reflected from the layer are recorded, analyzed in the Fourier domain and processed using our algorithms to obtain the quality of the bond line. The final results are displayed as bond line quality images.

An inversion algorithm developed allows simultaneous determination of interfacial spring and adhesive bulk properties from normal and oblique reflection spectra. It is based on a previously developed algorithm [2] dedicated to the determination of bulk properties (thickness, moduli, attenuation and density of embedded layers). The inversion procedure in this work is extended to include reconstruction of normal and transverse interfacial stiffness. The reflection spectrum depends on ten parameters: elastic moduli, thickness, density, longitudinal and shear attenuations and complex normal and shear interfacial spring constants (which

represent four parameters: two real and two imaginary):

$$\lambda, \mu, h, \rho, \alpha_l, \alpha_t, k_n = k_n^{'} + ik_n^{''}, k_t = k_t^{'} + ik_t^{''}. \quad (1)$$

Attenuation in the layer is often difficult to differentiate from losses at the interface (related to the imaginary part in the interfacial spring constants). Therefore, depending on which phenomenon is dominant, one can keep as unknown either the attenuation in the layer or the losses at the interfaces. The unknown variables are fully defined by two sets of nondimensional parameters and are determined from the measured normal and oblique spectra using a least squares optimization algorithm. To reconstruct the nondimensional parameters the least squares algorithm is used for the minimization of the sum of squared deviations between the calculated and the experimental reflection signatures.

In this way the linear method allows us to discriminate an environmentally degraded bond; however the contrast in the linear ultrasonic method is small, i.e. the difference in linear ultrasonic signature between the degraded and undegraded bond areas is small. This makes the linear ultrasonic bond line reconstruction method susceptible to error due to substrate property variations and misalignment errors. A second difficulty is the possible existence of static compressive residual stresses in the bond line induced by manufacturing processes. Under static compressive stress a small amplitude high frequency ultrasonic signal reflected from an imperfect bond may in some cases have the same characteristics as one reflected from a good bond. This is because the signal is too small to distinguish the imperfect interface, due to the continuity of ultrasonic stresses and displacements enforced at the interface by static compressive stresses.

To enhance interfacial property measurement and to relate the measurement to the local bond integrity

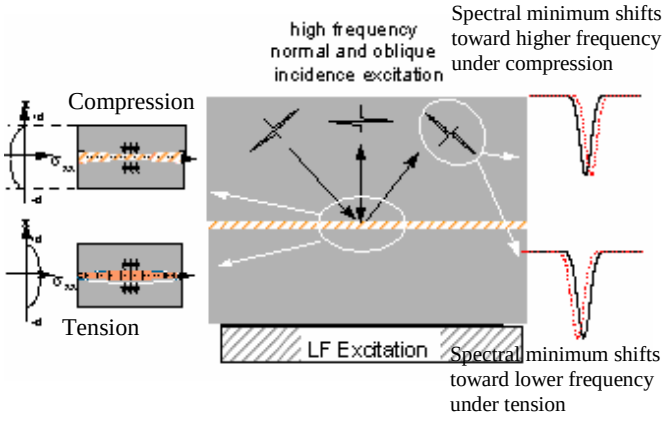

Figure 1: Proposed approach: Angle Beam Ultrasonic Spectroscopy of Adhesive Joints under thickness resonance parametric excitation.

degradation we use a stress modulation at the interface. We combine low frequency vibrations of the bonded structure with overlapped linear pulse echo dual beam ultrasonic reflection measurements as discussed above. When the bond is strong the interfacial stiffness is independent of low frequency stress (assuming that the stress is below the adhesion strength between adhesive and substrate). In the case of a poor bond, the interfacial stiffness decreases under the vibration tension due to the decreased density of molecular bonds (this is due to the fact that the load is transferred through fewer molecular bonds until it reaches the failure load). As a result the interfacial stiffness is different during compression and tension periods of low frequency cycles leading to a low frequency modulation of the spectral reflection minima of reflected ultrasonic signals.

Figure 1 shows our approach schematically. A tension/compression cycle is applied on the bond. The low frequency stress applied on the bondline is alternatively in compression or tension. The bond layer properties are evaluated during cycling using angle beam ultrasonic spectroscopy for different states of the stress of the bondline. This is achieved by controlling the synchronization between the low frequency continuous excitation of the structure and the high frequency pulsing used for the spectroscopic measurement. On the right, Fig. 1 schematically illustrates that for an imperfect bond the spectra minimum shifts under the loading.

Experimental apparatus

A dedicated experimental system for stress modulated angle beam ultrasonic spectroscopy was designed and built. The schematic of the experimental setup is shown in Figure 2a and the photo of the system in Figure 2b. The bonded sample is excited by the shaker and the vibration amplitude on the sample is measured by an accelerometer. The vibration was excited by piezoelectric, magnetostrictive and electrodynamic transducers in the frequency range 50 Hz-30 kHz. For perfect bonds no mixing is expected; for weak interfaces the boundary springs change under load leading to mixing higher and low frequency vibrations. The angle beam ultrasonic head include three 10MHz wide band transducers. To record the vibration mixing, the high frequency signals were digitized with a 12 bit 125 MHz digitizer followed by signal gating and FFT.

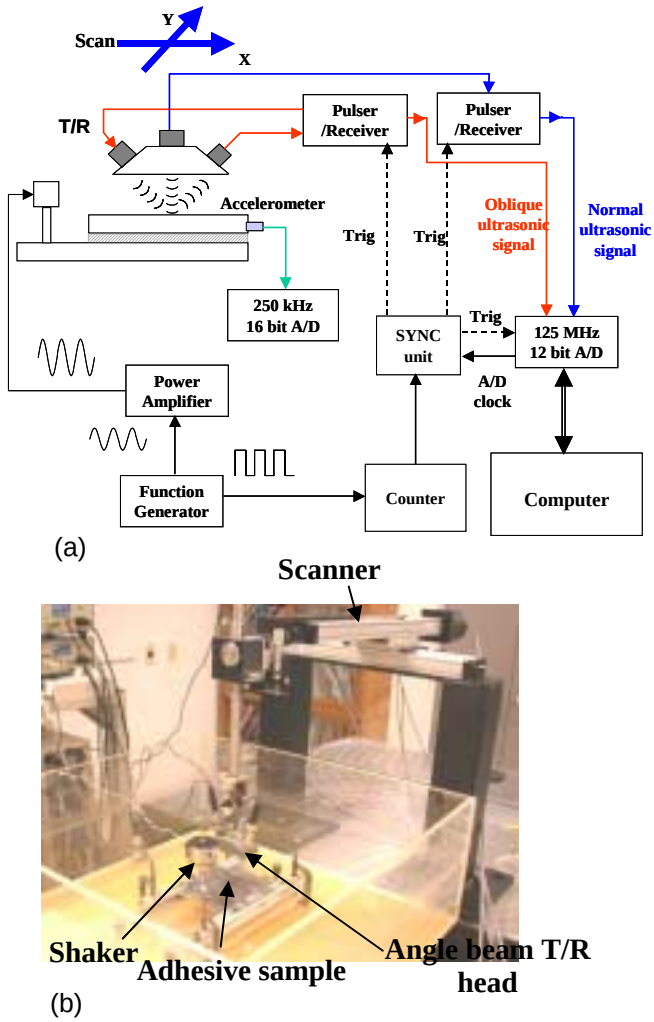

Figure 2: (a) Schematic of the experimental setup for stress modulated ultrasonic spectroscopy in vibration mixing mode. (b) Picture of the modulated angle beam ultrasonic spectroscopy system

Experimental results

Figure 3 shows a typical experimental reflection signal and spectrum from an adhesive bond. The gated signal in Fig. 3(a) corresponds to the reflection from the adhesive bondline. Its spectrum, after deconvolution with the transducer response, is shown in Fig. 3(b). The resonance frequency f_R and resonance depth A_R indicated in Fig. 3(b) are parameters which are related to the bondline properties. The computed variation of these parameters versus interfacial springs are shown in Fig. 4. In this simulation, we select the adhesive layer thickness 0.15mm, longitudinal velocity 2.5mm/μs, shear velocity 1.08 mm/μs, and density 1.1g/cm^3. As shown in Figure 4, when interfacial stiffness decreases, the resonance frequencies f_R are shifted to lower values. However, this shift is very small when the interfacial stiffness is higher than 10^{15}N/m^2. To improve the sensitivity of the angle beam spectroscopy method, we measure the spectra synchronically with an applied sinusoid modulation. For an imperfect interface, the spectra minimum (f_R) is shifted periodically with the modulation force while for a good bond this shift is practically zero. We illustrate the modulation method on an environmentally degraded adhesive bond. The experimental results were obtained for aluminum alloy bonded with commercial FM-73 structural adhesive. The adhesive joint samples were exposed to the environment until moisture penetration. To obtain the frequency modulation

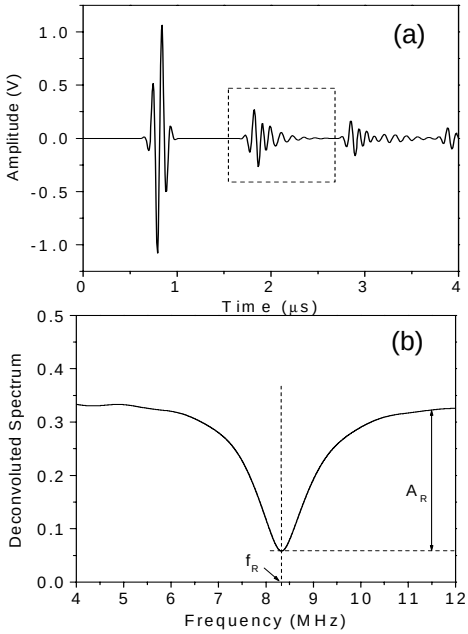

Figure 3: (a) A typical normal reflection signal from the embedded epoxy layer between aluminum substrates measured by a 10MHz wideband transducer. (b) deconvolved reflection spectrum of the bondline.

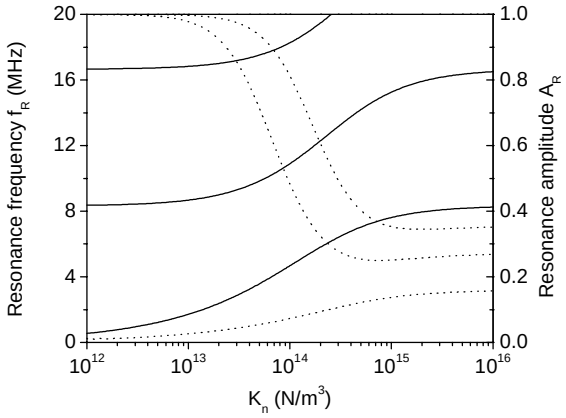

Figure 4: Simulated variation of the reflection spectra minima f_R and resonance depth A_R versus interfacial spring stiffness. Solid lines for resonance frequency f_R and dashed lines for resonance depth A_R. The adhesive layer has longitudinal velocity =2.5 mm/μs and thickness h=0.15 mm.

spectrum, we first record 40 time-domain signals for each low frequency cycle during a total of 50 modulation cycles. Then the deconvolved frequency spectra are obtained for each reflected signal from the bondline. From these spectra, the resonance frequency f_R and depth A_R are calculated to form the modulation signal. Finally, from this modulation signal the modulation spectrum is obtained.

Three examples of modulation spectra corresponding to different bond conditions are shown in Figure 5. The solid lines present the modulation spectra for normal incidence and the dashed lines for oblique. As one can see the frequency modulation index increases as the bond degradation increases. For degraded bonds, the resonance modulation amplitude is significant and the signal-to-noise ratio is larger than 33 dB. For bonds with intermediate bond degradation, the resonance modulation amplitude is reduced. For "good" bonds, the modulation amplitude is reduced to near noise level. The noise floor level of our system is around 0.01% which corresponds to about 1 kHz frequency shift. Figure 6 shows the results of measurement over a bonded area in scanning mode. The gray-level image represents the first harmonic modulation amplitude at 50 Hz. The dark gray level corresponds to high modulation amplitude. The modulation method has extremely high contrast level providing a zero signature for good bond. This is a significant advantage since one judges the existence of bond imperfections by comparing with zero (noise floor) corresponding to the good bonded areas.

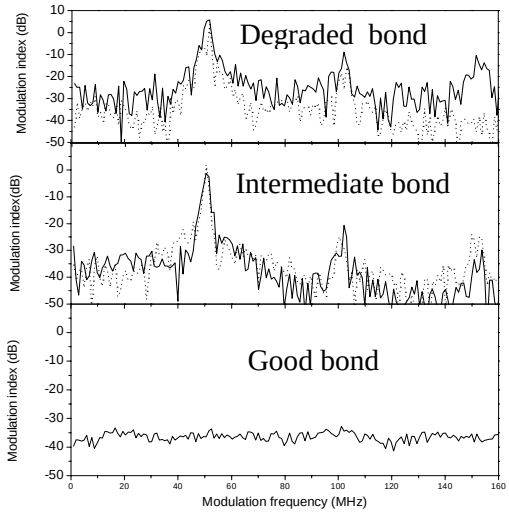

Figure 5: Examples of experimental resonance modulation spectra for three positions with different bond properties.

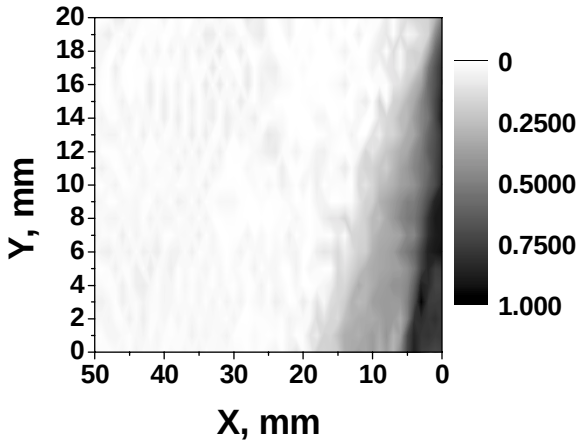

Figure 6: Measured resonance modulation amplitude for an aluminum adhesive bond. Scanning over 20mm×50mm area.

Conclusion

A nonlinear stress-modulated angle beam ultrasonic method for quantitative characterization of adhesive degradation has been developed. The method integrates the linear pulse echo angle beam ultrasonic technique with a low frequency modulation vibration. It is based on frequency modulation of the spectrum minima of the ultrasonic signal reflected from the bond. The results show that good quality (undamaged) bonds do not exhibit dependence of their ultrasonic signatures on the modulation; however, environmentally degraded or imperfect bonds exhibit a strong frequency modulation signature. The new technique provides very high image contrast between poor and good bonds

Acknowledgments

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