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A PARAMETRIC ULTRASONIC METHOD FOR THE EVALUATION OF ADHESIVE LAYER

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ABSTRACT

A parametric ultrasonic system for evaluation of interfaces has been developed. It is an enhancement of the Angle Beam Ultrasonic Spectroscopy (ABUS) by adding low-frequency modulation at the bonded interface which introduces a parametric variation of the interfacial stresses. The result is a frequency modulation of the reflected ultrasonic spectra. The ABUS method utilizes multiple broadband transducers interrogating an adhesive layer between two plates. From the reflected spectra with the aid of an analytical model, elastic constants, attenuation coefficients and geometrical parameters of the layer is obtained. When parametric modulation is added with a low frequency high amplitude transducer to the ABUS system, interfacial properties are also obtained from the parametric variation of the resonance frequency of the layer. It is demonstrated that good quality (undamaged) bonds do not exhibit ultrasonic signature dependence on the overlay of low frequency vibrations; however, environmentally degraded or imperfect bonds exhibit modulation of the spectral minima of the reflected ultrasonic signal. This parametric/nonlinear frequency modulation is characteristic of an imperfect interface. Thus, in a single test, the method provides linear (dual-beam pulse-echo) and nonlinear (angle-beam parametric frequency modulation) characterization of the adhesive bond properties.

1 INTRODUCTION

The integrity of an adhesive joint depends on the interfacial properties between the adhesive and adherents and on the bulk properties of the adhesive. Premature failure can be of either cohesive type, if fracture occurs in the interior of the adhesive layer itself, or adhesive type (interfacial) if fracture occurs on or very close to the adhesive/adherent interface. 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. Interfacial weakness of adhesive bonds is hidden from conventional linear inspection methods. Due to the difficulties in linear methods, nonlinear methods have been extensively investigated for earlier detection of adhesive degradation because adhesive failure is usually preceded by nonlinear phenomena [1-7]. One traditional nonlinear method is based on the higher harmonics generated by an ultrasonic wave transmitted through or reflected from an adhesive bond. It has been shown that the harmonic amplitude is closely correlated with the bond strength [1-3]. Another approach is to measure the effective bulk properties of the adhesive bond under quasi-static or lower frequency loading [4-7]. From a broader perspective one should note that nonlinear acoustic and thermal methods have been found promising for material diagnostics and damage detection in complex media since it has been established that imperfect interfaces associated with damage generate nonlinearity anomalously higher than in bulk solids. The related mechanisms were nonlinear Hertzian contact at microcrack surface asperities and/or clapping motions of the crack interfaces depending on the amplitude of the ultrasonic wave. A somewhat different approach in nonlinear ultrasonic diagnosis is modulation of an ultrasonic wave on an imperfect interface or a crack by an external dynamic load with a frequency lower than the probing ultrasonic wave. This produces crack closure modulation enhancing the detectability of the crack. The modulation can be induced thermally [8, 9] using laser pulse irradiation or by different mechanical means [7, 8-12].

In this paper we report an integrated (linear and non-linear) ultrasonic modulation method for quantitative characterization of bond integrity. The identification of the imperfect adhesive bond by the ultrasonic pulsed technique is enhanced by adding low frequency dynamic compression/tension vibrations at the bonded interface. It will be demonstrated that the parametric/nonlinear mixing between reflected high frequency ultrasonic pulse and low frequency dynamic vibration depends strongly on bond degradation. We build our approach on a linear angle beam ultrasonic spectroscopy method previously developed by us for determination of adhesive bonding layer properties and degradation. In this linear method the effective bulk properties of the adhesive layer, related to the bond degradation, are inversely determined from the ultrasonic reflection signatures [13-16]. The degraded interfaces between adhesive and substrate are described by a spring model [17,18]. An inversion algorithm has been developed which allows simultaneous determination of interfacial spring and adhesive bulk properties from normal and oblique reflection spectra [18]. When the normal and shear interfacial spring stiffnesses are of order greater than 10^{15} N/m^3, linear ultrasonic response indicates a good interfacial bond [17, 18]; 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 has been used as a quantitative parameter to describe the extent of interface damage in the linear ultrasonic method. In this paper for the data interpretation in the modulation method we have modified the linear spring stiffness concept assuming that the number of contacting springs depends on the modulation load.

2 METHOD CONCEPT

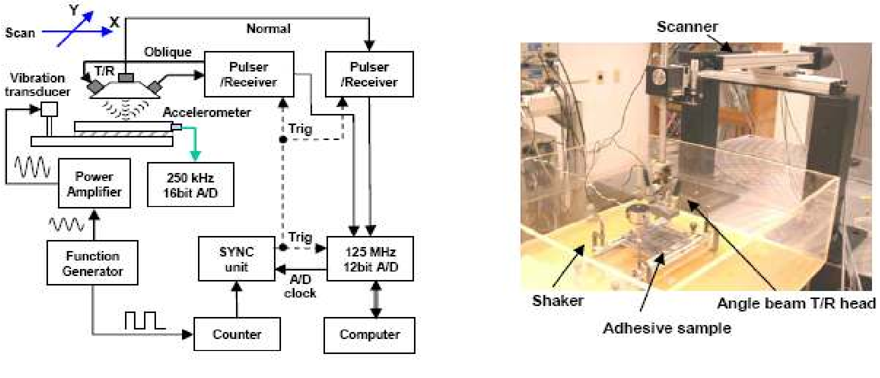
To enhance adhesive bond characterization we combine linear and nonlinear methods by incorporating pulse echo linear spectroscopy with parametric low frequency pulse/frequency modulation. In the linear approach [13-16], we use obliquely and normally incident ultrasonic beam spectroscopy. The two angle measurements allow decoupling of elastic moduli and thickness of the interfacial layer and the determination of the effective bulk properties of embedded layers (thickness, moduli, attenuation and density). For the practical realization of the method we have developed a dual beam scanning approach [14, 15]. 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 to obtain the quality of the bond line. An inversion algorithm developed allows simultaneous determination of interfacial springs and adhesive bulk properties from normal and oblique reflection spectra [16]. 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) [16]:

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

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 possess in some cases the same characteristics as one reflected from a good bond. This is because the ultrasonic stress amplitude is too small to overcome the compressive residual stress which results in the continuity of ultrasonic stresses and displacements across the interface. As a result in this case an imperfect interface is indistinguishable by the linear method from a perfect interface. To enhance interfacial property measurement and to relate the measurement to local bond integrity degradation we use 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. For a good bond the interfacial stiffness is independent of low frequency stress under our experimental conditions (assuming that the modulation stress is below the threshold where the nonlinear behavior of the good bond sets in). In the case of a poor bond, the interfacial stiffness decreases under the vibration tension.

3 EXPERIMENT

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 1(a) and a photo of the immersion system in Figure 1(b). The bonded sample is excited by the shaker and the vibration amplitude on the sample is measured by an accelerometer. Three different types of low frequency shakers were used for vibration excitation: piezoelectric, magnetostrictive and electrodynamic transducers covering the frequency range 50 Hz-30 kHz. For perfect bonds no mixing of vibrations with pulsed ultrasonic signals is expected; for weak interfaces the boundary springs change under load leading to amplitude and frequency modulation of ultrasonic signals by low frequency vibrations. The angle beam ultrasonic head includes three 10 MHz wide band transducers. The recorded high frequency signals were digitized with a 12 bit 125 MHz digitizer followed by signal gating and FFT.



(a) (b)

Figure 1: (a) Schematic of the experimental setup for stress modulated ultrasonic spectroscopy in vibration mixing mode. (b) Photo of the immersion modulated angle beam ultrasonic spectroscopy system.

Figure 2(a) shows the contact measurement system and Fig. 2(b) presents examples of the frequency modulation spectra for three locations with different bond quality, as they are displayed in real time on the computer monitor. As a result the interfacial stiffness changes during compression and tension periods of the low frequency cycles leading to a low frequency modulation of the spectral minima of reflected ultrasonic signals. Our experiments indicate that the frequency modulation due to the modulation-induced adhesive layer thickness change is negligible. To apply the modulation concept for characterization of adhesive bonds, we have performed modulated ultrasonic spectroscopy measurements on environmentally degraded joints. The experimental results were obtained for aluminum alloy bonded with commercial FM-73 adhesive. The adhesive joint samples were exposed to the environment until moisture penetration. Then they were attached rigidly to the shaker. For this experiment we selected modulation frequency 50Hz. 50 modulation cycles were used at each measurement point on the joint. For each cycle at 40 different time points of the cycle synchronized reflected pulses were acquired. Therefore in total of 2000 ultrasonic reflections from the interfaces are measured at one location on the bonded area. Figure 3 shows a typical experimental reflection signal and spectrum from an adhesive bond. The gated signal in Fig.3(a) corresponds to the adhesive bond and its spectrum, after deconvolution with the transducer response, is shown in Fig. 3(b). The frequency f_R and depth A_R corresponding to the spectrum minimum indicated in Fig. 3(b) are parameters which reflect the bondline properties. To illustrate the relation between the frequency modulation amplitude and adhesive bond degradation, the modulation resonance spectra for three positions with different bond conditions are shown in Figure 2(b). The solid lines present the modulation spectra for normal incidence and the dashed lines for oblique. As one can see the frequency modulation amplitude increases as 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 strength, the resonance modulation amplitude is reduced. For “good” bonds, the modulation amplitude is reduced to near the noise level. The noise floor level of our system is around 0.01% which corresponds to about 1 kHz frequency minimum shift. In Figure 2(b) modulation spectra are shown for three measurement points with different bond quality in the sample. The scanning over a 20x50 mm area was also performed in the dual beam reflection mode. The scanning results for the modulation index are displayed as gray level images in Figure 4(a, b). The gray level images represent the first harmonic modulation amplitude at 50 Hz. The dark gray levels correspond to high levels of the frequency modulation index. Figure 4(a) presents the frequency modulation scanning results at normal incidence and Figure 4(b) for oblique incidence. Both images indicate the transition from a highly degraded area (right bottom corner marked by ‘*D*’) to a good bond area (left top corner marked by ‘*G*’). The images have very high contrast with modulation index varying from 1% to nearly 0.01%. The images show that the damage is propagating inward from the edge area marked by ‘*D*’. The area marked by ‘*G*’ exhibits no visible damage. These results agree with the high-resolution C-scan image (50 MHz focused C-scan; it is not shown here). To compare with the modulation results we have made the C-scan with the same 10 MHz transducer by turning off the modulation vibrations and scanning the same area and acquiring 2,000 signals at each point for averaging (this provides the same number of pulses at every scanning point as in modulation data acquisition and processing).

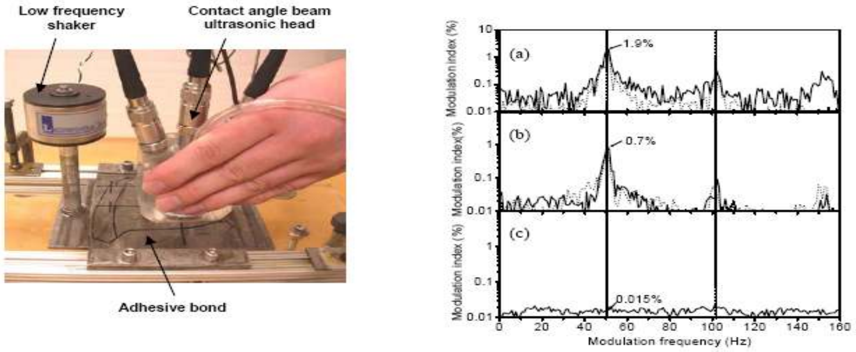


Figure 2: (a) Photo of the contact modulated angle beam ultrasonic spectroscopy system. (b) Examples of frequency modulation spectra for a degraded bond (top), intermediate bond (middle) and good bond.

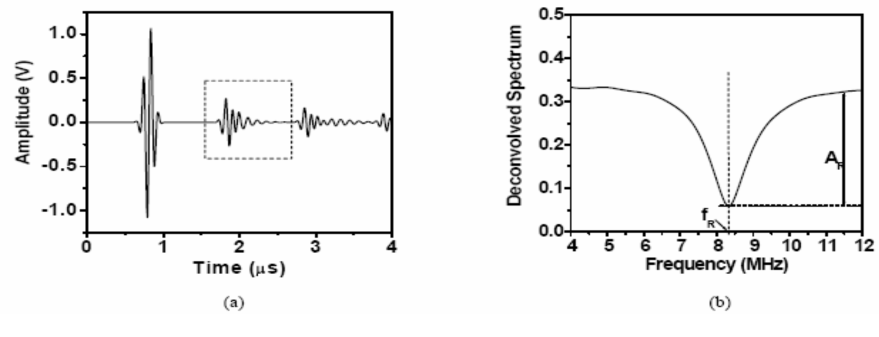
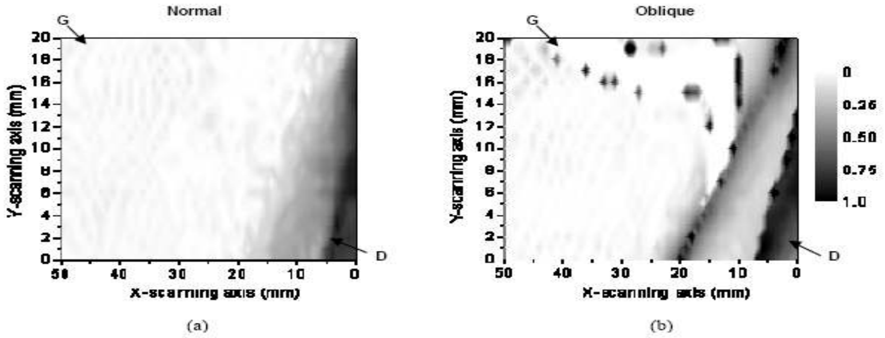


Figure 3: (a) A typical normal reflection signal from the aluminum epoxy layer bond measured by a 10MHz wideband transducer. (b) Deconvolved reflection spectrum of the bondline.



(a) (b)

Figure 4: (a) Gray level image of the resonance frequency modulation at normal incidence. (b) Gray level image of resonance frequency modulation at oblique measurement.

The gray-level image of the averaged peak amplitude (the C-scan image is not shown) has very low contrast and exhibits only the severely degraded area at the right bottom corner, *D*. The modulation method has much higher contrast providing nearly zero modulation level for a good bond. This is a significant advantage of the modulation method since one judges the existence of bond imperfections by comparing with zero (noise floor) corresponding to the good bond areas.

4 THEORY

For better understanding and quantification of the experimental results, a model is developed to simulate the stress-modulated angle beam spectroscopy method. To characterize the imperfect (weak) boundary layer at the bonded interface, we use an equivalent attractive force represented by an effective spring density. This is modeled by a set of identical attractive springs with variable length of interaction. The binding force *P*0 of the adhesive bond varies with the number of springs in contact. Thus the effective spring density becomes a function of pressure at the interface, lead into nonlinear behavior of the imperfect interface [19]. Under quasi-static stress modulation the boundary conditions for the higher frequency small amplitude probing ultrasound at the nonlinear interface may be written as

$$\sigma_n^+ = \sigma_n^- = K_n(P_0 + \Delta P(\Omega), \Delta u_n)\Delta u_n,$$

$$\sigma_t^+ = \sigma_t^- = K_t(P_0 + \Delta P(\Omega), \Delta u_n)\Delta u_t, \qquad (2)$$

where $\sigma+t$ and $\sigma-t$ are the shear stresses generated by the high frequency ultrasonic wave at the top and bottom surfaces of the interface respectively. Δ*un* and Δ*ut* are the normal and shear displacement jumps across the interface. The nonlinear interfacial springs *Ktn*, are functions of the static binding force *P*0, the low frequency dynamic modulation force Δ*P(*Ω) the displacement jump of the high frequency ultrasonic wave. The frequency f_R and amplitude A_R of the reflection spectral minimum (Figure 3) are the key parameters for the introduced stress-modulated angle-beam spectroscopy method. For given interfacial binding force *P*0 and modulation force Δ*P*, at each modulation time *T* the total quasi-static stress at the interface is P= *P*0+ Δ*P sin(2* ΩT) and the corresponding interfacial stiffnesses *Kt* obtained [19]. Using the boundary conditions (2) and considering the adhesive bond as a three layered structure with two imperfect interfaces between the adhesive and the substrate, the ultrasonic wave reflection and transmission problem is solved using a recursive stiffness matrix method [16]. The reflected time-domain pulses are calculated by the wave number integration technique using a recursive stiffness matrix method. The peak amplitude A_P, resonance frequency f_R and resonance depth A_R of the reflection minima are determined for each pulse forming a periodic function of the modulation time series. The reflected time-domain pulses are calculated by the wave number integration technique using a recursive stiffness matrix method. The peak amplitude A_P, resonance frequency f_R and resonance depth A_R of the reflection minima are determined for each pulse forming a periodic function of the modulation time series. The theoretical results show that the sensitivity of the resonance frequency modulation method is somewhat higher than that of the peak amplitude modulation. However, the main advantage of the frequency modulation approach comes from a different reason: the peak amplitude modulation is affected by the leakage of the modulation vibration, as a parasitic system noise, which arrives at the ultrasonic receiver and couples to the ultrasonic signal. This provides the threshold level noise for a peak amplitude modulation significantly above the 0.01% modulation index threshold achieved for the frequency modulation method which is free from this problem.

5 CONCLUSIONS

A nonlinear frequency-modulated ultrasonic method for quantitative characterization of interface degradation in adhesive bond has been developed. It is sensitive to the mechanical bond conditions on the interface under applied load. The imperfect interfaces are described using an effective nonlinear spring model. An experimental method incorporating high frequency pulsed dual-angle-beam ultrasonic measurements under low frequency vibrations of a bonded structure is described. The method utilizes parametric/nonlinear mixing between high and low frequencies. It is demonstrated that the effect of environmental degradation of adhesive bonds can be detected by this method. It is shown that good quality (undamaged) bonds do not exhibit dependence of their ultrasonic signatures on the overlay of low frequency vibration loads; however, environmentally degraded or imperfect bonds exhibit a strong modulation of the resonance frequencies of the adhesive layer presented in the normal and oblique reflection ultrasonic spectra.

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