APPLICATIONS OF GENERALIZED PULSE-ECHO FORMULAS FOR EVALUATION OF MULTILAYERED STRUCTURES

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INTRODUCTION

Multilayered composite structures and devices have become more popular and are now routinely introduced in advanced systems to reduce size and weight and to improve performance. However, because of the combined complexity of the materials and designs used in these systems, it is a significant challenge to determine the structural integrity and reliability of a specific structure or device using nondestructive evaluation (NDE).

X-ray, thermography and ultrasonics are the typical NDE methods used to evaluate the interface properties and the integrity of multilayered structures. Conventional X-ray and thermographic techniques and such exotic variations as tangential X-ray and time-resolved infrared are ideal for fast assessment of large areas of noncritical components. However, they are poor in lateral resolution and tend to be qualitative, rather than quantitative.

The fundamental principles of ultrasonic measurement, on the other hand, are based on elastic properties, and thus pulsed ultrasonic methods such as pulse-echo and through-transmission are considered quantitative. In a multilayered structure, however, the pulsed signal response is complicated by reverberations, and advanced algorithms are often needed for data acquisition and signal analysis to identify and extract the desired information [1,2].

We have derived time domain and amplitude equations that can be used to model the pulse response in pulsed ultrasonic applications. In this paper, we describe the use of these formulas to evaluate the integrity of bonded interfaces in two devices: an ultrasonic low-liquid-level sensor [3] for the propellant tanks of space-launch vehicles and an optical switch [4] for laser countermeasures.

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THEORETICAL ANALYSIS

We have derived generalized ultrasonic pulse-echo [5] and through-transmission [6] formulas to model the transit time and amplitude response of a pulse for an arbitrary n-layered structure. The theoretical time domain result can be used to determine and identify the exact time of arrival of the pulse from the critical interface with respect to when the pulse was initiated. The amplitude equation can be used to estimate the expected pulse amplitude response and compare the relative difference in amplitude across the selected section. These formulas can easily be programmed into a computer, and the theoretical pulse response determined based on the material properties of each layer of the structure.

In the following review, we reduced the generalized formulas to demonstrate their applicability to two-layered structures. As Fig. 1 shows, the system configurations of both the low-liquid-level sensor and the optical switch in the ultrasonic immersion experiments were modeled and analyzed as two-layered structures. The time equation for the two-layered structure can be expressed as

$$t_{mn} = m t_1 + n t_2 \tag{1}$$

where t=2d/v is the time it takes the pulse to make one round-trip through a thickness, d, with a wave velocity of v. The amplitude equation is expressed as

$$A_{mn} = A_0 T_{10} R_{10}^{m-1} R_{12}^{m+n} R_{23}^{n} e^{-2(m \alpha_1 d_1 + n \alpha_2 d_2)} \sum_{p=1}^{\min(m,n)} (-1)^{n-p} \binom{m}{p} \binom{n-1}{p-1} \left(\frac{1-R_{12}^2}{R_{12}^2} \right)^p \tag{2}$$

where A_0 is the initial pulse amplitude, R_{ij} and T_{ij} are the reflection and transmission coefficients for an ultrasonic pulse to propagate from medium i to medium j, respectively, and α is the attenuation factor.

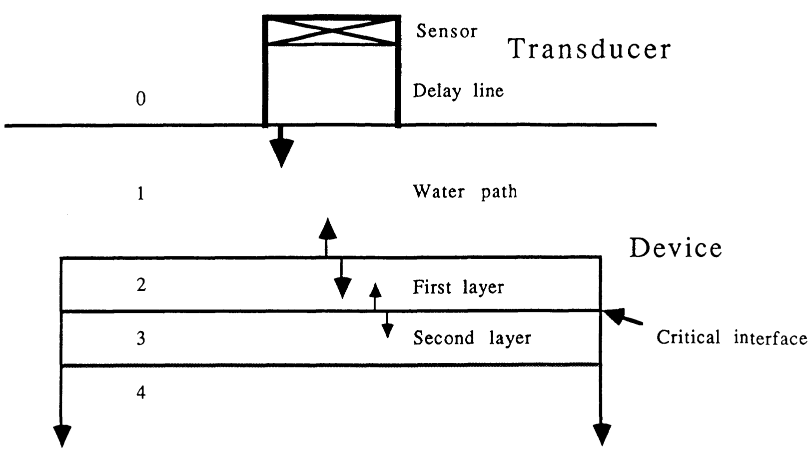


Fig. 1. System configuration of the two layered-structure in the immersion tests.

If we normalized the initial pulse to t_{1n} and A_{1n}, Eqs. (1) and (2) can be reduced to Eqs. (3) and (4). They are

$$t'_{1n} = t_{1n} - t_1 = n\,t_2 \tag{3}$$

and

$$A_{1n} = (A_0 T_{10} T_{12} e^{-2\alpha_1 d_1}) T_{21} R_{12}^{n-1} R_{23}^{n} e^{-2n\alpha_2 d_2} = A_{10} R_{12}^{n} R_{23}^{n} e^{-2n\alpha_2 d_2} \tag{4}$$

With the proper substitution of indices, Eqs. (3) and (4) are comparable to the time and amplitude equations for a one-layered structure, shown in Eqs. (5) and (6).

$$t_n = n\,t_1 \tag{5}$$

and

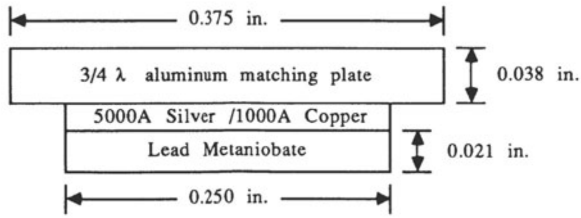
$$A_n = A_0 T_{10} R_{10}^{n-1} R_{12}^{n} e^{-2n\alpha_1 d_1} \tag{6}$$

The quality of the bonded interface is evaluated based on the variation in A_{1n} across the critical interface. This same argument can be used to reduce any arbitrary n-layered structure to one layer. In such an operation, we equalize the incident amplitude at the bonded interface for a quantitative evaluation of structural integrity.

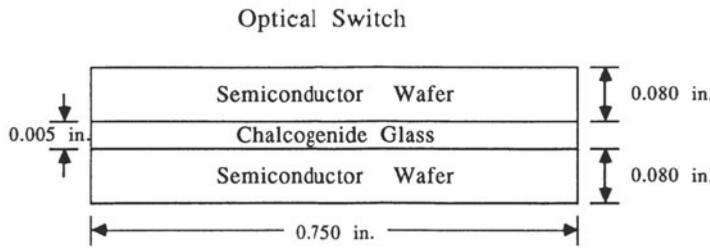
LABORATORY EXPERIMENTS

We applied the derived formulas and modeled the pulse response for an ultrasonic low-liquid-level sensor and an optical switch. Figure 2 shows the configurations of both devices. With the low-liquid-level sensor, the structural integrity of the bond between the piezoelectric element and the acoustic matching layer is critical to the function and service life of the device. Likewise, in the optical switch, the quality of the two bonds that join the chalcogenide glass layer to the two semiconductor wafers is critical to the performance of the device.

The block diagram of the pulse-echo acoustic imaging setup is shown in Fig. 3. The system consists of a mechanical scanning assembly, ultrasonic pulser/receiver and a computerized data acquisition system. The mechanical system is an in-house integrated scanning bridge with Clifton Precision stepping motors and controller. The high-frequency ultrasonic instruments are a Panametrics 5601T pulser/receiver, a 5608



(a)



(b)

Fig. 2. Structural configurations of a low-liquid-level sensor and an optical switch.

gated-peak detector, and a V390 50 MHz delay-line immersion transducer with a 1/2-in. focal length. A desk-top personal computer is configured for scan control as well as for data acquisition and image construction.

Figure 4 shows a typical oscilloscope trace for a low-liquid-level sensor. The critical interface (i.e., the bond between the piezoelectric element and acoustic matching plate) is identified to be

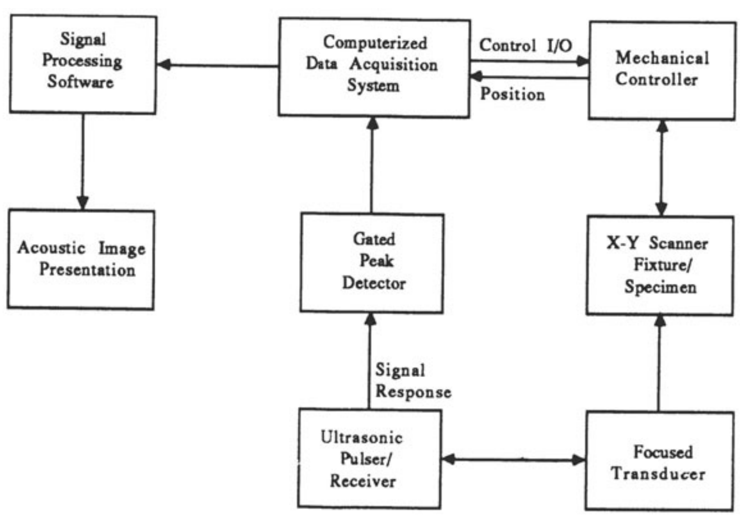


Fig. 3. Block diagram of the pulse-echo acoustic imaging setup.

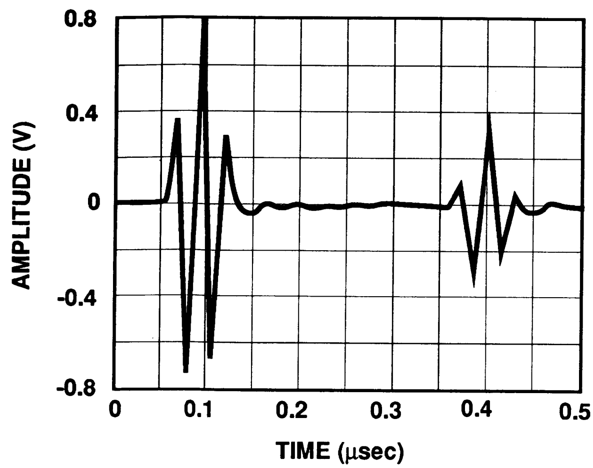


Fig. 4. Oscilloscope trace of the pulse-echo response of a low-liquid-level sensor.

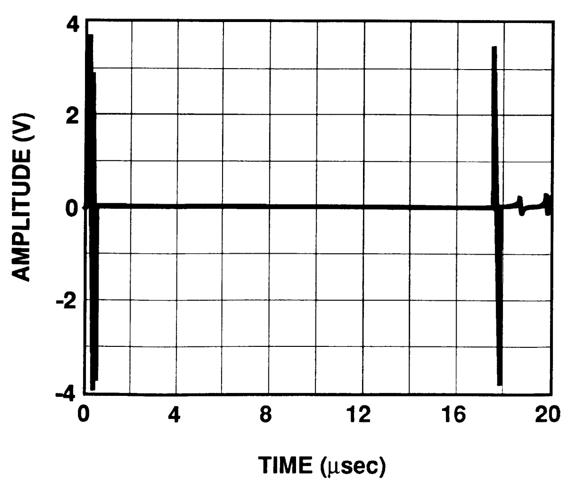


Fig. 5. Oscilloscope trace of the pulse-echo response of an optical switch.

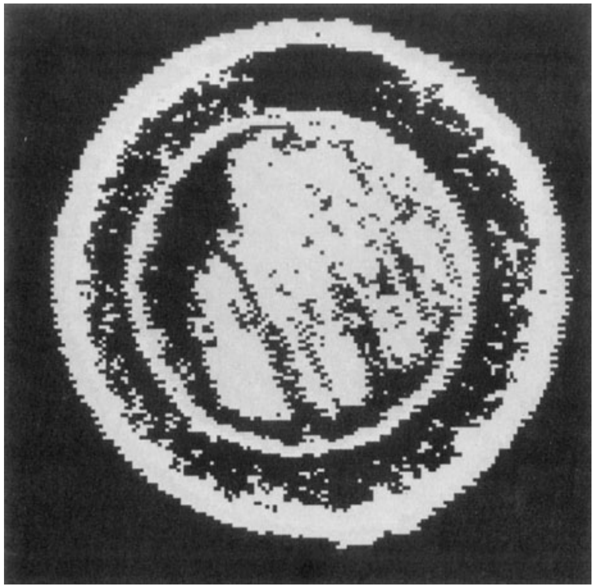


Fig. 6. An acoustic C-scan image of a low-liquid-level sensor showing the bonding quality of the critical interface.

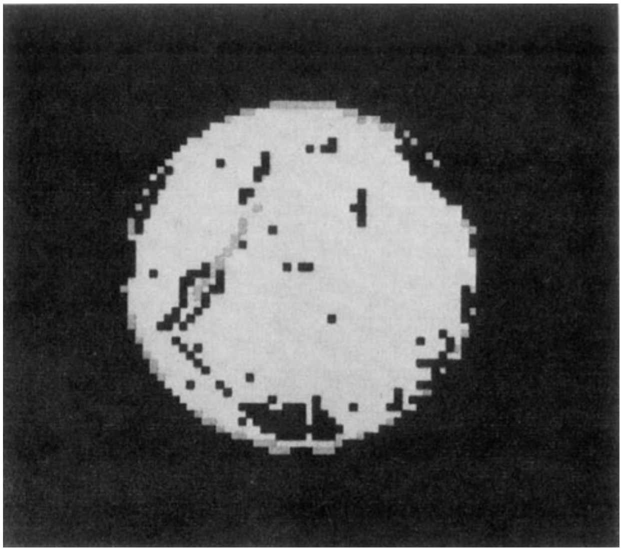
0.306 μs from the front surface of the matching plate. Figure 5 shows the oscilloscope trace of an optical switch. The 17.1-μs delay caused by the water layer is apparent in this figure. The critical interface for the optical switches is identified to be 0.751 μs from the front surface. The use of Eq. (3) to determine the time of arrival of the pulse from the critical interface is confirmed by these results.

Although an absolute amplitude cannot be obtained using Eq. (4) because of the complexity of the focused pulse reverberations in the devices, acoustic images can be generated to show the relative variations in amplitude at various sensing positions. The acoustic images in Figs. 6 and 7 clearly reveal the quality of the bonds at the critical interfaces of low-liquid-level sensor and an optical switch, respectively.

CONCLUSIONS

We have derived the time and amplitude equations for pulse-echo response of a multilayered structure. The time equation can be used to identify the critical interfaces, and the analysis of the amplitude equation provides the theoretical basis for ultrasonic evaluation of the interfaces of multilayered structures. The formulas can be incorporated into an expert system for automated data acquisition and analysis.

We have demonstrated the use of the time and amplitude equations to evaluate the critical joints of two electronic devices. Other potential applications of the equations include the determination of



BANDS: 0-40% 40-65% 65-80% 80-114%

Fig. 7. An acoustic C-scan image of an optical switch showing the quality of the critical interface bond.

structural integrity, and the modeling of wave propagation in multilayered materials and devices. The equations are applicable to both thick and thin specimens, but only if the pulse width is smaller than the thickness of each layer to minimize interference.

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