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Adhesive Layer Effects on PZT-induced Lamb Waves at Elevated Temperatures

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The role of the adhesive layer on PZT-induced Lamb wave propagation in structures exposed to elevated temperatures is presented in this article. Both experiments and numerical simulations were performed to study the effects of the adhesive layer on sensor signal at elevated temperatures. Experimentally, signals from PZT transducers with different adhesive thicknesses (40 and 120 μm) were investigated up to 500 kHz. In model simulations, the spectral element package (PESEA), which was developed previously, was adopted to simulate the test results. The simulations agreed with the experimental data quite well. Parametric studies were then performed using PESEA to evaluate the effect of adhesive layer on PZT-induced Lamb wave propagation at elevated temperatures as compared to other mechanical properties of the host structure and PZT materials; these studies revealed that the stiffness change of adhesive layer due to temperature is the most influential parameter for the change in sensor signals as compared to other mechanical properties, and that the thickness of the adhesive layer can affect a sensor signal in a different manner at elevated temperatures. This study shows PESEA can reasonably simulate the adhesive layer effect at elevated temperatures and hence can be a useful tool for understanding the behavior of Lamb wave propagation generated by adhesively bonded PZTs on structures.

Keywords adhesive layer · temperature effect · Lamb wave · nondestructive testing · spectral element method · structural health monitoring · shear lag effect · resonant effect.

1 Introduction

The acousto-ultrasound method, which uses built-in piezoelectric transducers, is promising because it can automatically inspect and interrogate structural damage in hard-to-access areas. Therefore, it has been widely studied in the structural health monitoring (SHM) field [1–6]. In an acousto-ultrasound system, diagnostic stress waves are generated by an adhesively bonded piezoelectric actuator, which converts electric voltage input into mechanical strain. While the waves travel through the structure under inspection, they interact with it. As a result, structural information is delivered to neighboring piezoelectric (PZT) sensors, which convert the mechanical strain into...
electric voltage output. If there is damage in the structure, the diagnostic waves interact with both the structure and the damage, thus carrying information about the structural health to the neighboring sensors. Damage detection algorithms extract damage information by comparing both the amplitude attenuation and arrival time delay of signals from the same structure before and after damage as shown in Figure 1. However, this technique is vulnerable to temperature variation in the environment because a signal can change even without ingress of damage.

Figure 2 shows the first symmetric mode in sensor signals collected at 25°C and 75°C. Although the same apparatus are used at both temperatures, the signals have significantly different amplitudes and arrival times. Therefore, a comprehensive understanding of temperature effects is essential before practical implementation of the acousto-ultrasound method using built-in piezoelectric transducers.

Several studies have been conducted on the temperature effects in PZT-induced Lamb wave propagation. Blaise and Chang [7] reported amplitude reduction and time delay of sensor signal at −90°C. Lee et al. [8] repeated experiments with damaged and undamaged aluminum plates to investigate hysteretic behavior, but did not find clear evidence of it. Their experiments demonstrated amplitude decrease and arrival time delay of S0 mode as the temperature was increased from 35°C to 75°C. Raghavan and Cesnik [9] studied the effects of elevated temperature on Lamb waves by theoretically simulating peak-to-peak amplitudes and arrival times of sensor signals. They then compared these to experimental data and determined that the arrival times correlated reasonably well with the experimental data, but the peak-to-peak amplitudes did not. The authors suggested adhesive layer effects, which were not included in the simulations, as a possible reason for the discrepancies [9]. di Scalea and Salamone [10] theoretically simulated with 2-D models the temperature effects from −40°C to 60°C. Adhesive layer effects were considered with a shear lag model, which caused signal amplitude reductions.

Recently, Ha and Chang [11] comprehensively studied adhesive layer effects on PZT sensor signals with spectral element simulations. Parameter studies with adhesive stiffness and thickness were conducted to investigate the physics of adhesive layers. An interesting finding was that the amplitude of a sensor signal may increase even with a lower shear modulus adhesive layer around the resonant frequency of a surface-mounted PZT, which is opposite to the shear lag effect. Elevated
temperature causes reduction in the shear modulus of the adhesive layer. Consequently, it is inferred that the adhesive layer at the elevated temperature may introduce more complicated phenomena than only signal amplitude reduction.

In this article, the effects on PZT-generated Lamb waves by elevated temperatures are studied using experiments and numerical simulations with the spectral element method (SEM). After the validations of the simulations, parametric studies will be followed to investigate the sensitivity of the adhesive shear modulus compared to other material parameters.

2 Validation of Numerical Simulations with Experiments

2.1 PESEA Spectral Element Simulations

The SEM has proven to be a very efficient tool to simulate high-frequency stress wave propagation due to its fast convergence rate [12–15]. It is very similar to the finite element method (FEM) in that it uses a weighted residual method and subdivides the whole spatial domain into pieces called elements. However, the adoption of high-order interpolation functions with a nodal quadrature, where integration points coincide with nodal points, makes the calculation of internal forces a lot more efficient and accurate than conventional FEM. In this study, a previously developed PZT-enabled spectral element analysis (PESEA) package is used [16,17]. The PESEA solves two coupled equations to simulate PZT-induced wave propagation in structures: (1) equation of motion in mechanical field and (2) Gauss equation in an electrical field. Detailed representations are shown in the previous paper [17]. The PESEA accepts arbitrary voltage waveform as input and produces voltage output from PZT sensors as a result of wave propagation in structures. Moreover, the PESEA is integrated with a commercial preprocessor to generate arbitrary structural geometries and a post-processor to visualize the transient dynamic wave motions in structures.

Figure 3 shows the configuration of a mesh for an adhesive layer. It was modeled by 12 spectral elements with 5th × 5th × 2nd order. In order to simulate PZT-induced Lamb wave propagation in an aluminum plate at elevated temperatures, the material properties of PZT, aluminum, and adhesive were changed in accordance with previous reports in the literature and MTS tests. Tables 1 and 2 indicate material property variations used in the simulations and their references. Unfortunately, the adhesive (Hysol9696) stiffness variation with temperature could not be found in the literature. Accordingly, tension tests were conducted using an MTS machine with a specimen made of the adhesive material to measure its Young’s modulus at elevated temperatures as shown in Figure 4. The specimen was heated to 100°C and covered in nonwoven polyester breather for insulation. A K-type thermocouple was attached to one side of the specimen to measure the current temperature. As the temperature of the specimen dropped from 75 to 25°C, the Young’s modulus was measured at eight discrete temperature points, and it was fitted with the second-order polynomial to obtain its variation as a function of temperature. The entire test lasted for approximately 15–20 min.

\[
E = 0.106 \times T^2 - 19.9 \times T + 2500
\]

Here \( T = \) Temperature (°C), \( E = \) Young’s modulus (MPa).

Poisson’s ratio was assumed to 0.4 for all temperatures considered.
2.2 Experimental Setup

In experiments for validation, an aluminum plate with 1.58 mm thickness was used. Dimensions of the plates are shown in Figure 5. PZT transducers with a thickness of 0.25 mm and a diameter of 6.35 mm were mounted to the surface using Hysol9696 adhesive (Henkel Inc.) as indicated in Figure 5. The sensor signals were collected with a 10 MS/s sampling rate in a pitch-catch mode. A five peak tone burst wave was used as an actuation signal. The specimen was heated in a high-temperature-controlled oven to simulate elevated environmental temperatures, and signals were measured from 25°C to 75°C. From the measurements, their maximum amplitudes were selected.

Experiments on temperature effects were conducted with: (1) thin adhesive layers under both the PZT actuator and sensor (thin adhesive layers), and (2) thick adhesive layers under both the PZT actuator and sensor (thick adhesive layers). Using the Hysol9696 adhesive film, thin and thick adhesive layers were controlled to be 40 and 120 µm, respectively.

2.3 Validation Result

To validate PESEA for temperature effects, simulations were conducted with the same configuration as the experimental setup in the previous section. In this validation, frequency responses of normalized maximum amplitudes at three different temperatures (25°C, 50°C, and 75°C) were compared for thin and thick adhesive layers. In both experiments and simulations, the normalized maximum amplitudes of the S0 mode were determined from the sensor signals with five peak-tone-burst inputs. The amplitudes were fitted with Gaussian curves in Microcal™ Orign to observe the shift of a resonant frequency due to temperature change.

Figure 6 shows variation of frequency response with thin adhesive layers at elevated temperatures. As temperature increases, the resonant frequency moves to a lower frequency in both experiment and simulation. As a result, amplitude increases
at 300, 350, and 400 kHz as temperature increases. This phenomenon has not been reported by any researcher previously. The simulation correlates well with the experiment.

Frequency response with thick adhesive layers is shown in Figure 7. A resonant peak with thick adhesive layers is located at a little lower frequency than with thin adhesive layers. While reduction of peak amplitude is negligible when thin layers are used, thick adhesive layers demonstrate observable reductions in peak amplitude at elevated temperatures. Moreover, thick layers cause less peak shift variability. Consequently, amplitude increase at elevated temperatures is barely observed over all frequencies with thick adhesive layers. Although the simulation locates the resonant peak to be at a slightly lower frequency than the experiment, it shows a reasonably correlated result in the trend of amplitude change at elevated temperatures.

It is important to determine the reason for the trends shown in Figures 6 and 7. Thus, parametric studies with PESEA simulation were conducted to investigate the effects of major parameters in the next section.

### 3 Parametric Studies

The objective of parametric studies is to understand the effects of major parameters at elevated temperatures. As the first step, material properties, which change with temperature, were selected as parameters. Sensor signals were simulated at two different temperatures, 25°C and 75°C. The material parameters were varied individually to study the effect of each parameter on the amplitude of the
sensor signal. Based on the simulations, Young's modulus of aluminum ($E_{Al}$), Young’s modulus of PZT ($E_{PZT}$), shear modulus of adhesive ($E_{Ad}$), PZT coupling coefficient ($d_{31}$), and PZT electric permittivity ($e_{33}$) were determined to be the major parameters, which significantly affect signal amplitude.

Parametric studies for PZT transducers with thin (40 μm) and thick (120 μm) adhesive layers were conducted to understand the effects of each parameter on sensor signals. Figures 8 and 9 show percent change of maximum amplitudes at 150, 350, and 500 kHz excitations. The percent change was calculated with respect to the maximum amplitude at 25°C.

Parametric study with thin adhesive layers is shown in Figure 8. The most influential parameter is the adhesive shear modulus ($G_{Ad}$). The decrease in adhesive shear modulus at a higher temperature (75°C) causes the amplitude increase at 350 kHz while it causes the amplitude to decrease at 150 and 500 kHz. It is well correlated with the trend of amplitude variation shown in Figure 6. The shear modulus reduction moves the resonant frequency of surface-mounted PZTs closer to 350 kHz, and thus increases the amplitude. The shift of the resonant frequency with the variation of the shear modulus was also reported in the previous study [11]. However, the amplitude at 500 kHz decreases as the resonant frequency recedes from 500 kHz.

Figure 9 shows the result of parametric study with thick adhesive layers. The most influential parameter is also the adhesive shear modulus ($G_{Ad}$). However, the pattern of amplitude change is quite different from the thin adhesive case. Decrease in adhesive shear modulus at a higher temperature (75°C) causes amplitude reductions at all frequencies. This phenomenon can be explained by the shear lag effect, which causes reduction in signal amplitude with a thicker and softer adhesive layer.
From the parametric studies, we have demonstrated that the most important parameter affecting the amplitude of sensor signals is the adhesive shear modulus. Accordingly, it is significant to investigate variations of signal amplitudes with a different type of adhesive.

4 Amplitude Variation with a Different Type of Adhesive

Cw2400 (ITW CHEMTRONICS, Inc.), which is two-part conductive epoxy, was selected to investigate the pattern of signal change at elevated temperatures. To measure Young’s modulus ($E$), a compression test was conducted in the MTS machine on a $22 \times 45 \times 5.6 \text{ mm}^2$ small epoxy specimen. The measurement was conducted as described above in Figure 4 (Hysol9696). However, an approximate value of the Young’s modulus at $25^\circ\text{C}$ could be obtained because the test coupon was small in dimensions.

The following variation of $E$ was obtained:

$$E = 5.6799 \times 10^{-5} \times T^2 - 1.7534 \times 10^{-2} \times T + 1.6192$$

where $T =$ temperature ($^\circ\text{C}$) and $E =$ Young’s modulus (GPa).

Poisson’s ratio was assumed to 0.4 for all temperatures considered.

Shear moduli of Hysol 9696 and cw2400 are summarized in Table 3.

Frequency responses with thin cw2400 adhesive layers are plotted in Figure 10. The same configuration as the previous simulations was used. Overall trends with cw2400 are different from those with Hysol9696. The amplitude reduction rate of resonant peaks at higher temperatures is significantly higher than that with Hysol9696, which is common with thin cw2400 adhesive case. In particular, higher temperatures always cause lower signal amplitudes at all frequencies due to increased shear lag effect.

Consequently, the shear lag effect becomes more dominant, and it causes more reduction in the signal amplitude as temperature increases.

Figure 11 shows simulated frequency responses with thick cw2400 adhesive layers. The amplitude reduction rate of resonant peaks at elevated temperatures is significantly higher than that with Hysol9696, which is common with thin cw2400 adhesive case. In particular, higher temperatures always cause lower signal amplitudes at all frequencies due to increased shear lag effect.

Table 3 Variation of shear modulus.

<table>
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<tr>
<th></th>
<th>25°C</th>
<th>75°C</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hysol9696</td>
<td>739 MPa</td>
<td>573 MPa</td>
<td>22.5 %</td>
</tr>
<tr>
<td>Cw2400</td>
<td>434 MPa</td>
<td>223 MPa</td>
<td>48.6 %</td>
</tr>
</tbody>
</table>

Figure 10 Frequency response with thin adhesive layers (40 $\mu$m).

Figure 11 Frequency response with thick adhesive (120 $\mu$m).
5 Frequency Response of Thick PZTs

We have demonstrated that the adhesive layer is the most significant factor affecting the signal amplitude at elevated temperatures. According to a previous study on adhesive layer effects [11], the thickness of a PZT also affects the variation pattern of the amplitude together with the adhesive shear modulus. PESEA simulations were performed in order to investigate the effects of the PZT thickness. To separate the PZT thickness effect, the same configuration and adhesive (Hysol9696) as in Section 2 was used except for relatively thick PZTs with a thickness of 0.75 mm and a diameter of 6.35 mm.

Figure 12 shows simulation results for thick PZTs with thin adhesive layers. Different trends of the amplitude variation from Figure 6 (a thin PZT with thin adhesive) are observed; the signal amplitude decreases at all frequencies without a noticeable shift of the resonant peak as temperature increases. Patterns of maximum amplitude changes for thin and thick PZTs with thin adhesive layers are shown in Figure 13. Maximum amplitude ratio is calculated relative to values at 25°C. As temperature increases, signal amplitude of the thin PZTs decreases at 200 kHz due to the shear lag effect and increases at 300 and 400 kHz due to the shift of the resonant peak. However, the amplitude of the thick PZTs decreases at all frequencies because there is no significant shift of the resonant peak as stated above.

Figure 14 shows simulation results for a thick PZT with thick adhesive layers. It is very
similar to the results for the thick PZTs with thin adhesive layers in that the signal amplitude is reduced at all frequencies at elevated temperatures without a noticeable shift of the resonant peak. However, the resonant peaks are located at a slightly lower frequency. Maximum amplitude ratio for thin and thick PZTs with thick adhesive layers is shown in Figure 15. For the thin PZTs with thick adhesive layers, signal amplitude decreases at 200 kHz due to the shear lag effect as temperature increases. Due to the shift of the resonant peak, the amplitude increases at 300 kHz and decreases at 400 kHz. However, the amplitude with the thick PZTs decreases at all frequencies.

6 Conclusions

In this article, the effects of adhesive layers on sensor signals with temperature variations, which have been neglected in previous studies, were studied. Experiments showed that adhesive layer thickness can affect sensor signals in different patterns. Numerical analysis with PESEA could simulate this phenomenon. From parametric studies with PESEA simulations, it was found that adhesive stiffness is very sensitive to temperature variation and significantly affects sensor signal. Moreover, amplitude variation with a different type of adhesive and PZT thickness effects were investigated.
Acknowledgments

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References