Characterization of the bond quality of adhesive plates utilizing zero-group-velocity Lamb waves measured by a laser ultrasonics technique

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Abstract
The bonding quality of an adhesive component was estimated using the frequency of zero-group-velocity (ZGV) Lamb waves, which can be generated and detected with a laser ultrasonic technique. Two distinct peaks corresponding to ZGV Lamb waves in the amplitude spectrum were obtained for well- and weak-bonded adhesive plate samples. The frequency difference between the measured low frequency mode and the calculated frequency, which can be obtained by assuming a continuous stress and strain at a bonding interface, linearly increased with shear strength, as obtained by the shear-tensile test. The frequency of ZGV Lamb waves was also calculated with reduced shear modulus of the bonding layer to express a weak bonding, and the change in the calculated frequency in low frequency ZGV Lamb waves showed a similar tendency to that in measured one.

Key words : Bond quality, Adhesive bond, Zero-group-velocity Lamb waves, Laser ultrasonics

1. Introduction
Adhesive bonding is expected to be used for jointing space frame components in motor vehicles (Barnes and Pashby 2000) because its components are lightweight and have a possibility of high joint stiffness compared to spot-welds (Addreley 1988). On the other hand, the bond quality of an adhesive bond is sensitive to pre-treatment of the adhered surfaces (Bishopp 1988). If there are contaminants on the surface, such as lubricants and oils, the bond strength reduces significantly. Non-destructive evaluation techniques offer various methods for estimating the quality of industrial products. However, there is no commercially available NDT method for estimating bond quality.

Ultrasonic inspection is expected to be a vital tool for estimating bond quality. Certain researchers have reported that reflection coefficients from normal and oblique incident longitudinal and shear waves to the bonding layer have a potential to evaluate bond quality (Liastsis et. al, 2006). Further, interface waves propagating through the interface between two adhered components is reported as an indicator of bond quality (Huang and Rokhlin 1994). However, these methods are not yet common because the propagation behavior of the interface waves is complicated. Recently, it was reported that zero-group-velocity (ZGV) Lamb waves, which cannot propagate but their phase velocity remain finite value, are sensitive to the elastic properties and thickness of a thin plate (Holland and Chimenti 2003). Additionally, the ZGV Lamb waves can be measured with non-contact methods such as the laser ultrasonic method and air-coupled transducers and can be applied in an industrial field. The ZGV Lamb waves also have potential for estimating the bond quality of adhesive bonds (Colrennec et. al., 2010). However, the detailed relationship between the bond quality or strength and the ZGV Lamb wave is unclear. One of the authors has tried to characterize bond quality of brazed samples with ZGV Lamb waves (Cho et. al., 2014). In the brazed samples, poor bond quality was caused by defects along the interface between the brazed layer and a substrate. The frequency in one of ZGV Lamb modes for the brazed samples was significantly changed for bonding strength. However, the quality of adhesive
bonding could be weakened by an improper pre-treatment of the adhered condition even if there is no defect along the interface. It would be important to characterize the bond quality of the adhesive bonding without interfacial defects.

In this study, characterization of the bond quality for two 3-mm aluminum plates glued with a commercially available epoxy adhesive was performed with resonant frequencies of the ZGV Lamb waves, and the results were compared with the bond strength obtained using the shear-tensile test.

2. Zero-group-velocity Lamb waves in a bonded sample

Figure 1 shows the calculated dispersion relation for Lamb waves propagating in a jointing component composed of two identical aluminum alloy plates with thicknesses of 3-mm and a 0.09-mm bonding layer with the software DISPERSE (Pavlakovic and Lowe 2005). This system was identical to the sample for measuring the ZGV Lamb wave in this study. The Young's modulus, Poisson's ratio, and density of the aluminum plate and the bonding layer used in the calculation were 70.7 GPa, 0.337, and 2.7×10^3 kg/m^3 (Pavlakovic and Lowe 2005) and 3.94 GPa, 0.392, and 1.17×10^3 kg/m^3, respectively. The elastic properties of the bonding layer were determined from longitudinal and shear wave velocities measured using a transmission method for the disk composed of only the epoxy agent with a thickness of 20 mm at 2 MHz and density measured by Archimedeian method. The three points in Fig.1 indicated by the arrows where the gradient of the curves is zero, are corresponding to the ZGV Lamb waves. At these points, the phase velocity calculated from the quotient of the wavenumber and frequency remains finite. The frequency of ZGV Lamb waves as well as phase velocities of Lamb waves can reflect the bonding quality and the elastic properties, density, and thickness of each layer.

![Fig.1 Dispersion relationship for a bonded sample consisting of two Al alloy plates (A2017-T4) and an epoxy adhesive.](image)

3. Samples and experimental setup

We prepared a lap-joint type sample composed of two 3-mm aluminum alloy plates and a commercially available two-component epoxy adhesive agent (Araldite®), as shown in Fig.2. The dimensions of the two aluminum alloy (JIS: A2017-T4) plates were 100 mm × 25 mm × 3 mm, and the adhesive area was 25 mm × 13 mm. Poor-bonding quality samples were prepared by contaminating the polished adherend surface with grease, and good-quality samples were prepared by roughening the surface with #30 abrasive papers and degreasing with acetone. The grease used in this study was silicone grease for lubricant. The epoxy agent was cured at 60 °C for 1 hour in a hot drying furnace. The edge shape of the agent around the lapping area formed with a round shaped stick to have the same concentrated factor on the edge during shear tensile testing. The numbers of the well- and weak-bonded samples were 11 and 18, respectively. The agent thickness was measured by subtracting the total thickness of the
sample after curing with the two aluminum alloy plates as adherends with a micrometer.

A laser ultrasonic technique was utilized for measuring ZGV Lamb waves, as shown in Fig.3. A Q-switched YAG laser with a wavelength of 1024 nm and duration time of 10 ns was used to generate ZGV Lamb waves. Laser energy was controlled to remain below the ablation threshold of the sample and was 20 mJ. The diameter of the YAG laser spot was 3 mm. Generated ZGV Lamb waves were detected with a laser interferometer that is capable of detecting out-of-plane displacement up to 40 MHz. The probe beam of the interferometer (spot size: 0.3 mm) was irradiated on the epicenter of the generation point. The output signal of the interferometer was filtered with a high-pass filter with a cutoff frequency of 600 kHz, and then, it was captured with a digital oscilloscope with 32 time-averaging data points. The sampling interval and points were 10 ns and 16384, respectively. To measure a distribution of bond quality over the adhesive area, the sample was set on a two-dimensional mechanical stage and the waves were detected at 8 points × 3 lines (24 points) on the adhesive area with 2-mm intervals. Tensile testing for evaluating shear adhesive strength was carried out after the ZGV Lamb wave measurement. The crosshead speed was 0.1 mm/min.

4. Experimental results

Figure 4 shows the diagrams of shear stress and displacement of the crosshead of the loading machine for well- and weak-bonded samples. The tensile speed was set to 0.1 mm/min. The shear strength of the sample was determined from the maximum stress on the diagram. No large void was conformed in the adhesive layer by observing the adhesive surface after tensile testing.
Figure 5 shows the measured shear strength for the all well- and weak-bonded samples. The strength of the well-bonded samples ranged in 14 MPa to 19 MPa. In weak-bonded samples, the strength was scattered between 2 MPa and 18 MPa and some weak-bonded samples showed almost the same strength of the well-bonded samples because it may be caused by lack of grease.

![Shear strength graph](image)

**Fig.5** Measured shear strength by shear tensile test for the well- and weak-bonded samples.

Figure 6 shows the waveforms of ZGV Lamb waves for the samples corresponding to Fig.4 and their frequency spectra. The spectrum was calculated using a Fourier transform. A zero-padding treatment was applied in the Fourier transform to improve the frequency resolution. In this study, the frequency resolution was 0.76 kHz. The first large pulse waves after 8 $\mu$s, corresponding to the trigger timing of the YAG laser, are longitudinal and shear waves transmitting through the sample; these are followed by oscillating waves composed of resonant ZGV Lamb waves and propagation mode Lamb waves reflected at the sample edges. Two distinct peaks at around 0.95 MHz and 3 MHz in the spectrum for both samples are observed; those frequencies correspond to the resonant frequencies of ZGV Lamb waves and are almost the same as the calculated frequencies of the higher two modes in the ZGV Lamb waves shown in Fig.1. Additionally, those two frequencies are not in a relation of an integer ratio. Therefore, those two frequency peaks are corresponding to the frequency peaks of ZGV Lamb waves. The low frequency peak is called mode $\alpha$, and the high frequency peak is mode $\beta$.

![Waveform and frequency spectra](image)

**Fig.6** Detected waveforms for well- and weak-bonded samples and their frequency spectra.
In our previous study for characterizing the bond quality for brazed samples, the amplitude in a certain mode of ZGV Lamb waves was significantly changed for the weak-bonded sample. It could be caused by defects along an interface between a substrate and a brazing layer. However, the amplitude was also affected by the surface condition of laser irradiation area. In this study, as shown in Fig.6 (c), (d), the amplitude of mode $\alpha$ decreases and mode $\beta$ increases when the shear strength decreases. The change in the amplitude between well- and weak-bonded samples is small and it is comparable to the change in the amplitude at each measuring point on the one sample. In each mode, the resonant frequency in the weak-bonded sample was slightly shifted to a lower frequency compared to those for the well-bonded sample. However, the ZGV Lamb wave frequency is changed by not only the bond quality but also the thickness of the adhesive layer. To characterize the bond quality, the difference between the measured and calculated ZGV Lamb wave frequency at the same thickness of the adhesive layer for each measurement point was evaluated and was shown in the relationship of the shear strength obtained by the shear tensile testing after ZGV Lamb wave measurement. A calculation was carried out using the software DISPERSE; in the calculation, the stress and strain across the interface between the adhesive layer and the two substrates are assumed to be continuous, which implies a perfect bond condition. Figure 7 shows the relationship between the frequency differences between the measured and calculated ones and the shear strength. The square symbol indicates frequency difference for the weak-bonded sample with mirror finished surface and grease contamination. The triangle symbol is for the well-bonded sample with #30 polishing. The frequency differences tends to increase with decreasing shear strength in mode $\alpha$. This means that a slip condition that allows the strain along the interface to be discontinuous was present in the low-adhesive strength sample (Schoenberg 1980). Each symbol forming the horizontal line on the same shear strength shows the measured ZGV Lamb wave frequency at the each measuring point on each sample. The frequency variation over the measuring point for each sample was in the range of approximately 0.03 MHz shown as horizontally aligned symbols in Fig.7. The measured frequencies of ZGV Lamb waves at the same point were reproduced well within 2.5 kHz, much lower than the frequency variation on each sample. Therefore, this variation implies that the bond quality is not uniform over one adhesive area. The lines in Fig.7 were determined by fitting the relation between the minimum measured frequency in each sample (the leftmost symbol among each horizontally aligned symbol in Fig. 7) and the corresponding shear strength with a least mean-squares method because the shear strength could be governed by the area with the minimum strength in the adhesive area. The correlation coefficient of $R^2$ for the line for mode $\alpha$ was 0.86, and the maximum frequency difference was correlated with the shear strength. On the other hand, most of the frequencies in mode $\beta$ were in the range of -0.03 MHz to 0.04 MHz and were independent of the shear strength.

![Fig.7 Relationship between measured shear strength and frequency difference between analytical and measured ZGV.](image)

To study the dependence of the frequency of ZGV Lamb waves on the shear strength, the sensitivity of the frequency to bond quality was calculated. Bond quality can be expressed as the degree of discontinuity of the
displacement at the interface between the substrate and the bonding layer which is corresponding to interface stiffness (Schoenberg 1980). Velocities of ultrasonic waves are linked to elastic properties of a material. However, the strength is not one of the elastic properties. On the other hand, the interfacial stiffness which is one of elastic characteristics at the interface changes ultrasonic velocities, and could be related to the bonding strength. Therefore, relation between the ZGV Lamb wave’s frequency and the interfacial stiffness is discussed.

The displacement discontinuity can be realized by reducing the shear elastic constant of the bonding layer in calculations to change interfacial stiffness of the sample. The shear modulus of the bonding layer was reduced from its original value (1.4 GPa) to 0.7 GPa, and the frequency of ZGV Lamb waves was calculated with the software DISPERSE. The thickness of a layer was set at 0.09 mm. Figure 8 shows the calculated frequency of ZGV Lamb waves in both mode $\alpha$ and $\beta$ as a function of the shear modulus of the bonding layer. The vertical axis shows the frequency difference from the calculated one with the original shear modulus of 1.4 GPa. The calculated frequency linearly decreased with the shear modulus of the bonding layer, and showed a similar relation to the measured frequency difference in mode $\alpha$. The measured frequency change in mode $\alpha$ could be caused by change in interface stiffness in the adhesive layer. The change in the frequency difference in mode $\alpha$ is 4 times larger than that in mode $\beta$ in the calculation. In mode $\beta$, the change in calculated frequency is small, and the change in experimental measurement could not be identified as shown in Fig.7 (b). This showed that mode $\alpha$ could be more sensitive to the bonding quality than mode $\beta$. To further study the behavior of ZGV Lamb waves with respect to bonding quality, a numerical wave propagation simulation that can visualize the vibration of the ZGV Lamb wave will be performed.

![Graph](image)

**Fig.8** Calculated frequency change for the mode $\alpha$ and $\beta$ of ZGV Lamb waves as a function of shear modulus in the bonding layer.

5. **conclusions**

To characterize the bonding quality of an adhesive agent sandwiched between two identical aluminum alloy plates, a zero-group-velocity (ZGV) Lamb wave measurement was carried out with a laser ultrasonic technique. The results are summarized below.

1. Two distinct peaks in the frequency spectrum corresponding to ZGV Lamb waves were measured for well- and weak-bonded samples; the frequencies for the weak-bonded sample decreased compared to those for the well-bonded sample.

2. The frequency difference in the low-frequency mode at around 0.9 MHz between the measured and calculated frequency, which can be obtained by assuming stress and strain at the bonding interface to be continuous, increased...
with decreasing shear strength of the samples, obtained by a shear-tensile test. On the other hand, the measured high-frequency mode did not have a relationship with shear strength.

3. The frequency of ZGV Lamb waves with weak bonding quality was calculated by reducing the shear modulus of the bonding layer to express the displacement discontinuity at the bonding interface. The calculated frequency decreased with the shear modulus, and showed a similar tendency to the measured one. The frequency difference between the calculated ZGV frequencies with the original shear modulus and a reduced one for the low-frequency mode is four times larger than that for the high-frequency mode of ZGV Lamb waves.

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References