Research article

Detection of disbonds in adhesively bonded aluminum plates using laser-generated shear acoustic waves

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Adhesively bonded metals are increasingly used in many industries. Inspecting these parts remains challenging for modern non-destructive testing techniques. Laser ultrasound (LU) has shown great potential in high-resolution imaging of carbon-reinforced composites. For metals, excitation of longitudinal waves is inefficient without surface ablation. However, shear waves can be efficiently generated in the thermo-elastic regime and used to image defects in metallic structures. Here we present a compact LU system consisting of a high repetition rate diode-pumped laser to excite shear waves and noncontact detection with a highly sensitive fiber optic Sagnac interferometer to inspect adhesively bonded aluminum plates. Multiphysics finite difference simulations are performed to optimize the measurement configuration. Damage detection is performed for a structure consisting of three aluminum plates bonded with an epoxy film. Defects are simulated by a thin Teflon film. It is shown that the proposed technique can efficiently localize defects in both adhesion layers.

1. Introduction

Adhesively bonded multilayer metal plates are commonly used in many industries, including nuclear energy, automotive and aerospace. Adhesive bonding provides several advantages, e.g. stress distribution over the entire bonding area, reduced weight, and the ability to join dissimilar materials [1]. Nevertheless, it is also susceptible to various types of defects, including voids, disbonds, porosity or poor adhesion.

Several defect types in the adhesive layer, such as porosity or voids, can be detected using X-Ray radiography [1]. However, this method requires double-sided access and cannot easily detect non-volumetric defects, such as disbonds and delaminations.

In contrast, ultrasound (US) methods provide good sensitivity to a variety of defects in bonded structures [1,2]. Despite this, interpreting US scans is challenging for multi-layered structures such as typical aircraft components containing between 2 and 4 bonded plates with 0.5–4 mm thickness. As a result, through-transmission inspection is still frequently used, even though it cannot provide in-depth resolution. Its main disadvantage is the need for two-sided access and perfect transducer alignment. Additionally, coupling agents are required to manage the high impedance mismatch between air and metals.

Conventional US pulse-echo inspection of these multilayer structures is very difficult due to numerous wave reflections and mode conversions at boundaries. At low frequencies, mode-converted and reflected waves superimpose to produce Lamb waves. The dispersive character of these waves makes them sensitive to local changes of thickness or material properties. This property can be exploited in model-based parametric analysis to estimate bonding layer properties by matching measured results to theoretical dispersion curves [3]. Another imaging approach maps local wavenumber-frequency pairs of specific Lamb modes to the measurement grid using a wavenumber filter bank. Its effectiveness has been demonstrated for both defects in homogenous plates [4,5], metal honeycomb structures [6] as well as composite delaminations [4,7].

Another common NDT method for bonded structures is ultrasonic spectroscopy [8] based on measuring the electrical impedance of a contact US transducer as a function of frequency near resonance. Structural and material alterations of the adhesive layer change the measured impedance. However, the probe must be mechanically coupled to the inspected surface, and spatial resolution is reduced because of the low US frequency used.

Laser ultrasound (LU) overcomes numerous limitations of conventional US testing and has become increasingly popular as a result. Laser

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pulse excite broadband US signals, significantly improving the resolution compared to contact probes. Broadband longitudinal waves can be used to image individual plies in structures made of carbon-reinforced plastics [9,10], obtaining images similar to X-ray computed tomography [11]. However, due to the small skin depth of laser light absorption in metals, longitudinal waves are not efficiently generated in the direction normal to the surface without surface ablation or a constraining layer [12]. Therefore, common LU methods appropriate for composites are generally not applicable to metals.

Nevertheless, different US wave modes can be excited in metals by pulsed laser radiation. Laser-generated surface [13], shear [14,15], and Lamb waves [16–18] have been used for multiple applications in metals. In addition, LU can be used to excite and detect so-called Zero Group Velocity (ZGV) modes. They exhibit great sensitivity to local changes in plate thickness, bond quality, or material properties [19–23]. However, interpreting the ZGV resonance for multi-layered structures is usually very complex due to multiple resonances. Thus, without comprehensive numerical simulation, it is challenging to characterize defects based on ZGV resonances in bonded structures [21,22].

The source-receiver distance has to be adjusted to optimize system sensitivity for alternate propagation modes. In Ref. [18], the amplitude of laser-generated Lamb waves was measured over a fixed short distance from the excitation spot, and both excitation and receiving lasers were scanned over the surface of a two-layer epoxy-bonded plate. Disbonds were detected based on changes in amplitude of the Lamb mode over the damaged area. This analysis was done at relatively low frequencies (in the 0.1–0.3 MHz range), which limits spatial resolution and the ability to characterize defects, especially for multilayer structures.

Ref. [15] used LU-generated shear waves (SW) to evaluate disbonds in a relatively thick (4 mm) two-layered structure. However, experimental results were obtained only when ablation generated US signals.

In this work, we employ the thermoelastic regime of US shear wave excitation at the sample surface (with no induced ablation) to detect disbonds in multilayer aluminum structures. Complex samples consisting of three epoxy-bonded aluminum plates, with artificial defects created with Teflon inserts at both interfaces, are used to test all methods.

A line source excited shear waves with sufficient sensitivity to detect defects. It produces shear waves propagating in a direction oblique to the surface but over a spatial extent that reduces diffraction effects and deposits larger laser energy to the sample at levels below the ablation point [24,25]. In addition, a highly sensitive fiber-optic Sagnac interferometer detected US signals [26,27].

Laser-generated shear waves propagate at an oblique angle in the inspected structure. If a discontinuity lies along their propagation path, a reflected wave propagates to the surface where it can be detected. Knowing the wave generation angle and the depth of anticipated defects, the position of optical sensors can be adjusted to maximize system sensitivity. The optimal source-detector distance was selected based on multiphysics simulations of laser wave generation and propagation. Measurements show that the optimal distance can be selected for each bond layer to maximize defect detection at high spatial resolution.

2. Theory

2.1. Laser generated shear waves

For non-ablative laser excitation of shear waves, the LU system operates in the thermo-elastic regime. Elastic waves are generated from stresses induced by heating a small part of the material through light absorption [28]. These stresses are small enough to avoid damaging the sample.

For an isotropic material, the excitation mechanism in the thermoelastic regime (neglecting the heat produced by mechanical deformation, and the second derivative of the temperature \( T \)) is described by the following set of coupled differential equations [25]:

\[
\begin{align*}
&k \nabla^2 T = \rho c_V \dot{T} - q \\
&\rho \nabla^2 u + (\lambda + \mu) \nabla(\nabla \cdot u) = \rho \ddot{u} + \beta \nabla T
\end{align*}
\]

where \( k \) is the thermal conductivity coefficient, \( T \) is the temperature in the material, \( \rho \) is the material density, \( c_V \) is the specific heat at constant volume, \( q \) is the power density of the heat source created by laser irradiation, \( \ddot{u} \) is the unknown displacement vector due to the thermoelastic effect, \( \lambda \) and \( \mu \) are the Lame constants, and \( \beta \) is the thermo-acoustic coupling constant related to the linear thermal expansion coefficient.
Fig. 2. (a) Space-time representation of simulated signals obtained as the difference between out-of-plane responses for pristine and damage cases (Model 1 – Air). Combinations of labels L and S denote reflected or mode-converted longitudinal or shear waves respectively. (b) Envelope of signals presented in panel (a) with circled area of maximal difference between signals. Panels (c) and (d) corresponds to Model 2 – Air. Panels (e), (f) and panels (g), (h) refer to Model 1 – Teflon and Model 2 – Teflon, respectively.
\[ \alpha T = \beta \]

\[ (3\lambda + 2\mu)\alpha T. \]

Eq. (1) is a general form of the heat diffusion equation, derived from Fourier’s law of thermal conduction applying energy conservation. It relates heat transfer through a material to the temperature gradient and the change in thermal energy of the body. Eq. (2) describes elastic wave propagation due to thermal expansion of the irradiated volume.

### 2.2. Model based source-receiver distance optimization

For structural inspection, understanding the propagation characteristics of generated elastic waves is critical. For homogenous metallic structures, the directivity patterns of longitudinal and shear waves generated by a laser source can be derived analytically for a point \([12, 29]\) and an infinite line source \([24, 25]\). For more complex scenarios, e.g., structures composed of multiple thin plates or complicated excitation patterns, numerical procedures such as finite difference (FD) \([30, 31]\) or finite element \([32, 33]\) methods can be used. Here, the elastic displacements generated by a laser heat source are obtained from a two-dimensional (2D) coupled thermoelasticity model developed using a local interaction simulation approach (LISA) \([34, 35]\). Details are presented in Appendix A.

As shown in Fig. 1a, two 2D multilayer models were investigated. They contain three aluminum plates (density \(\rho = 2700 \text{ kg/m}^3\), Young’s modulus \(E = 68.9 \text{ GPa}\), Poisson’s ratio \(\nu = 0.33\)) with thicknesses of 1, 1.25, and 3.5 mm, and length of 20 mm. The epoxy bond (\(\rho = 1540 \text{ kg/m}^3\), \(E = 3.5 \text{ GPa}\), \(\nu = 0.33\)) between consecutive plates was 4.2 \(\mu\text{m}\) thick.

The time step and space discretization were chosen as 0.5 ns and 4.2 \(\mu\text{m}\), respectively, satisfying the Courant stability criterion to ensure the accuracy and efficiency of the simulation. A 15 ns Gaussian laser pulse with a spatial width of 150 \(\mu\text{m}\) and peak energy \(E_p = 1 \text{ mJ}\) was applied at the top surface of the model in the center of the structure to approximate the heat source.

Defects were simulated as 4 mm-long inserts in the first and second epoxy layers for Model 1 and 2, respectively. Two damage scenarios were considered for both models assuming air or Teflon’s material properties for the inserts. These configurations were used to resemble experimental conditions in which defects were introduced to the samples using Teflon films. Such an approach is commonly used to create controlled defects in multi-layered structures. The inserts often trap air.
between adherents, which creates a large impedance difference at the boundary. If the inserts are tightly squeezed, there is acoustic coupling between the layers, and the defect can be categorized as a foreign object inclusion. Snapshots of the wavefields for models 1 and 2 at $t = 0.9 \mu s$ are presented in Fig. 1b and c, respectively. Additionally, movies showing the full simulation can be seen as Supplementary data in Appendix 1 and Appendix 2. These simulations clearly show the directivity of generated longitudinal (L) and shear (S) waves, as well as a strong Rayleigh (R) wave propagating along the excited surface. Some minor wave reflections can be observed as consecutive waves pass through the bonding layers. In contrast, a strong interaction between the disbond and the S-L wave is evident for both damage cases. For Model 1, $t = 0.9 \mu s$ corresponds to a time step when the S-wave reflected from the defect appears on the plate’s surface, while for Model 2, the generated S-wave interacts with the disbond.

To determine the optimal distance between source and receiver for detecting US reflections from a disbond at a given depth, out-of-plane velocity signals (i.e., time derivative of the displacement) were collected at a set of spatial locations at the top surface of the models (as indicated in Fig. 1a). To remove waves not altered by the defect, additional simulation was performed using an intact model. Reference signals from these models were subtracted from the damage cases, producing the space-time maps of damage-reflected waves in Fig. 2. The left panels of Fig. 2(a,c,e,g) present space-time representations of simulated signals. The arrival times are parabolic with distance for waves reflected by the defect. Based on the estimated theoretical time of flights (TOF), all traces were successfully identified as reflections or mode-conversions of shear and longitudinal waves. To illustrate the maximum difference between intact and damage models, envelopes of the signals from the left panels are presented in the right panels of Fig. 2 (b,d,f,h). Clearly, both the model with air and the model with Teflon give comparable results. The main difference is in the reflected/mode converted wave amplitude ratio. Nevertheless, in all cases, a significant contribution from reflected shear waves can be seen in Fig. 2b, d, f, and h in the area circled with a dashed line.

For Model 1, in both air (Fig. 2b) and Teflon (Fig. 2f) damage scenarios, the shear wave reflection can be observed at approximately a 2 mm source-receiver distance and 0.9 $\mu s$ TOF. For the air gap, the S-wave reflection is the global maximum in the figure. For the Teflon model, several areas of higher magnitudes corresponding to S to L (S-L) converted modes can be observed.

For both damage scenarios, i.e., air (Fig. 2d) and Teflon (Fig. 2h) evaluated for Model 2, two areas of high magnitude can be distinguished. A strong S-wave reflection is observed for TOF = 1.9 $\mu s$, and a significant shear mode converted to longitudinal (S-L) wave is seen for TOF of approximately 1.6 $\mu s$. In both cases, maxima occur approximately at a 4 mm source-receiver spacing; therefore, it was selected as the optimal distance to evaluate this interface.

2.3. Numerical resolution study

As shown in the previous sub-section, the source-receiver distance has to be adjusted to optimize shear wave reflection due to oblique wave propagation. Similarly, the resolution of this technique is expected to depend on the depth of the defect location.

A 2D 6 mm thick model, consisting of two bonded aluminum plates with material properties corresponding to the model from Section 2.2, was created (Fig. 3a). To consider different scenarios, the thickness of the aluminum layers varied. The epoxy bond was placed at depths ranging from 1 to 5 mm. The defect with material properties corresponding to air was simulated as a 4 mm-long insert in the center of the epoxy layer. The length of the model I also varied (from 20 to 32 mm) for different depths to ensure that reflections from edges will not appear in the recorded signals.

In the first step, the source-receiver distance was optimized for each defect depth using the procedure described in Section 2.2. Then, the situation resembling experimental scanning was performed: a set of simulations for multiple positions of the source-receiver pair stepped by 0.1 mm along the horizontal axis ($x$-axis) was performed. Out-of-plane velocity signals were collected for all runs resulting in a B-scan image. Signals from a pristine model were subtracted from the damage cases to separate shear waves reflected from the air gap, as shown in Fig. 3a. Maximum amplitudes, corresponding to the time of flight of the reflected shear waves, were used to create the profiles illustrated in Fig. 3c.

To evaluate the resolution of this technique, a sigmoid function expressed as

$$C(x) = a \left( \frac{1}{1 + \exp \left( \frac{1}{b \cdot (x - c)} \right) } \right)$$

was used to fit the amplitude profiles [36]. The resolution was obtained using the full width at half amplitude of the derived $C(x)$ profile, as illustrated in Fig. 3c.

Resolution profiles illustrated in Fig. 3c were collected for every defect location yielding the dependence presented in Fig. 3d. The dependence is approximately linear over almost the entire range. An artifact corresponding to the 4 mm location depth of the defect stems from multiple reflection for the mode-converted S-L wave disturbing the simulated B-scan. Thus, the resolution is depth-dependent; the ability to
resolve smaller defects decays with depth.

3. Experiments

3.1. Experimental setup

To evaluate the proposed damage imaging method, two samples containing three aluminum plates (1, 1.27, and 3.56 mm-thick) bonded

Fig. 5. The procedure of inverse filtering. (a) Typical B-scan. (b) Reference signal, obtained by averaging time waveforms over an undamaged area. (c) Reference spectrum. (d) Typical signal from the damaged area. (e) Spectrum of the signal in the damaged area. (f) Ratio of signal spectra recorded in the damaged and undamaged areas, band-pass filter (BPF) used to surpress high frequency components of the ratio and the result of filtration (Filtered ratio). (g) Deconvolved signal from damaged area obtained by inverse Fourier transform of the filtered ratio. (h) B-scan after the deconvolution.
with the epoxy film were investigated. Teflon inserts (15 × 15 mm) were placed between the first and second epoxy layers for sample 1 and 2, respectively.

Experiments were performed using an LU pump-probe system, detailed in Refs. [37,38], with a Sagnac interferometer [26,27] on receive. As illustrated in Fig. 4, pulses from a diode-pumped nanosecond laser were focused using a 50 mm cylindrical lens to form a thin excitation line (150 μm x 7 mm) on the sample surface. Based on the numerical simulations, the source-receiver distances \( d \) were set to 2 mm and 4 mm for sample 1 and 2, respectively. Pump laser pulses were triggered from the translation stage to obtain position-synchronized excitation and, thus, achieve uniform spatial sampling during scanning. The pulse energy was about 1 mJ, and the pulse-repetition frequency varied from 0 to 1 kHz. Therefore, when the translation speed reached 20 mm/s, the lateral resolution was equal to 0.02 mm (i.e., 20 μm). The results were initially low-pass filtered using a cut-off frequency of 10 MHz and spatially averaged using a 2D Gaussian window (21 × 21 points, \( \sigma = 10 \) points). Next, all signals were normalized to the peak

![CAD model of sample 1](image1.png)

**Fig. 6.** (a) CAD model of sample 1, and an example of data acquired for this sample. (b) Waveforms acquired from the damaged (red) and undamaged (blue) areas. (c) B scan image scanned over the damaged area. (d) Temporal responses obtained by inverse filtration of signals presented in panel (b). (e) B-scan from panel (c) after deconvolution of the time histories. Blue and red vertical lines indicate positions for corresponding waveforms displayed in panels (b) and (d). Horizontal line corresponds to \( t = 0.95 \mu s \) as predicted in simulations for the S-S wave arrival. C-scan corresponding to this arrival time is presented in Fig. 7.
signal amplitude at the surface, representing the amplitude of the induced surface wave. Since surface wave generation is expected to be constant over the sample, this normalization step compensates for spatial variability of light reflectivity from the sample surface.

3.2. Inverse filtering

Laser pulses absorbed by a metallic plate generate multiple wave modes, with the dominant mode a surface wave. As noted in the numerical analyses, signals obtained from damaged and undamaged cases were simply subtracted to reveal differences. For experimental data, however, signals vary from point to point, and simple subtraction is ineffective. To isolate shear waves reflected from the inspected bond interface, an inverse filter was developed.

As illustrated in Fig. 5b, a reference signal is first created by averaging signals over an undamaged area. Next, the signal is transformed to the frequency domain (Fig. 5c) and becomes the denominator of the inverse filter. However, the averaged response has a limited bandwidth and, when placed in the denominator, a significant increase in amplitude occurs. To isolate shear waves reflected from the inspected bond interface, an inverse filter was developed. A Gaussian-window-shaped filter was applied using the poles resulting from nearly zero-amplitude spectral components of the band-pass (BPF) is added to the inverse filter numerator to suppress components greatly amplify the noise in the deconvolved signal. Therefore, a band-pass (BPF) is added to the inverse filter numerator to suppress poles resulting from nearly zero-amplitude spectral components of the denominator. A Gaussian-window-shaped filter was applied using the following equation:

\[ F(f) = (1 - \exp \left( -\left(\frac{f}{f_0}\right)^2 \right) \exp \left( -\left(\frac{f}{f_1}\right)^2 - \left(\frac{f}{f_2}\right)^4 \right). \] (4)

The parameters \( f_0 \) and \( f_1 \) are adjusted according to the bandwidth of acquired experimental data. The results presented below were not particularly sensitive to the exact choices of \( f_0 \) and \( f_1 \) as long as they captured the primary spectral range of the averaged signal.

The inverse filter is then applied to all recorded signals in the frequency domain. After Fourier transformation of the signal, its spectrum is divided by the reference spectrum and multiplied by a BPF, as illustrated in Fig. 5f, to produce the deconvolved signal.

A more comprehensive explanation of this technique, with specific filter parameter values for specific cases, is provided in subsequent sections.

4. Results

4.1. Sample 1

Based on the results of simulations presented in Section 2.2.2, the transmit-receiver distance was set to 2 mm for Sample 1. Examples of time-domain signals obtained at positions with and without defect contributions are presented in Fig. 6b. Although these signals are quite similar overall, an extra spike for the signal recorded in the defect region is clearly observed at about \( t = 0.95 \mu s \), which corresponds well to theoretical predictions for the first arrival of a shear wave reflecting from the defect located 1 mm beneath the surface.

The upper part of a B-scan, obtained from scanning over an area containing a defect (see Fig. 6c), corresponds to a surface wave that can be seen as a horizontal bright line for \( t = 0.72 \mu s \). The reflected shear wave signal arriving at \( t = 0.95 \mu s \) can be recognized in the B-scan in the X-region between roughly 7 mm and 22 mm. It is interesting that a scattering pattern from defect edges is also clear in the B-scan.

To reveal differences between damaged and undamaged areas, inverse filtering was applied to the temporal signals presented in Fig. 6b and the results are shown in Fig. 6d. The cut-off frequencies of the filter, according to the Eq. (4), were set to \( f_0 = 100 \) kHz and \( f_1 = 8.42 \) MHz. As seen in Fig. 6d, applying inverse filtration to the reference signal results in a Gaussian pulse centered at \( t = 0 \), which is the impulse response of the BPF. The width of the pulse is proportional to the bandwidth of the Gaussian BPF used in the filter.

Applying the inverse filter to signals from both damaged and undamaged areas results in a near-Gaussian shaped pulse at \( t = 0.72 \mu s \) corresponding to the filter impulse response, as shown in Fig. 6d. For the signal from the undamaged area, the remaining part of the time trace is flat and equals nearly zero as the structural response is almost identical to the reference signal. On the other hand, additional peaks can be observed in the filtered response from the damaged area. The maximum peak after the main pulse occurs at \( t = 0.95 \mu s \), which corresponds well to the expected time of flight of the shear wave reflected from the depth of 1 mm, where the defect is located. Additional peaks seen in Fig. 6d are related to multiple reflections, and mode-conversion of shear and longitudinal waves.

Inverse filtering was repeated for all recorded A-scans, and the filtered B-scan is presented in Fig. 6e. The defect area is now clearly visible compared to the unfiltered B-scan in Fig. 6c. Several horizontal lines indicate multiple modes reflecting from the defect. The area of the highest intensity can be observed, as expected, at \( t = 0.95 \mu s \).

The complete dataset consisting of 1250 B-scans was processed using the proposed algorithm. After that, each C-scan (horizontal slice of the 3D data at each time step) was averaged with a 2D Gaussian window using the following parameters: window size \( 21 \times 21 \) and alpha = 1 (resulting in standard deviation equal to 10). The amplitude of signals at the time corresponding to shear wave reflection arrival (\( t = 0.95 \mu s \)) is presented as a C-scan in Fig. 7, revealing the insert in the bonding area with its geometry well preserved.

4.2. Sample 2

The same procedure was applied to sample 2, containing a Teflon insert at the second adhesive layer. To inspect the interface at a depth of approx. 2.3 mm (thickness of two aluminum plates and one epoxy layer), the source-receiver distance was set to 4 mm as predicted by simulations.

Looking at time-domain signals obtained from undamaged and damaged areas, presented in Fig. 8b, most of the waveforms are coherent, with slight variations starting at \( t = 2 \mu s \). In addition, the B-scan image presented in Fig. 8c shows relatively uniform data without a clear damage indication.

Inverse filtering was applied to all signals again using \( f_0 = 100 \) kHz and \( f_1 = 8.42 \) MHz. In Fig. 8d, the waveforms of Fig. 8b are presented after inverse filtering. As predicted from simulations, two areas of maximum defect reflections are observed. One, related to the S-L wave arriving at \( t = 1.62 \mu s \), and the second corresponding to shear wave signal arriving at \( t = 1.89 \mu s \). Slight oscillations are also seen in the
undamaged waveforms, indicating that inverse filtering is not perfect.

The deconvolved B-scan of Fig. 8c is presented in Fig. 8e. The area corresponding to the defect is now clearly seen. Again, the C-scans were averaged using the same 2D Gaussian window as for sample 1 (window size $21 \times 21$ and alpha $= 1$). The amplitudes of the deconvolved signals at $t = 1.62$ μs and $t = 1.89$ μs obtained for the entire data set are presented as C-scans in Fig. 9(a) and (b) respectively. From the images, both the location and size of the defect are clearly discernible.

5. Discussion

In bulk materials, the directivity pattern of laser generated US can be evaluated analytically. For multi-layered thin plates, however, this approach is not accurate due to near-field effects. In this paper, therefore, a multiphysics model based on LISA was developed. It accurately describes laser-generated ultrasound waves in complex structures and their interactions with structural heterogeneities. It can be used to
waves should propagate at an angle of about 30° from the normal to the surface. Based on this assumption, the source-receiver distance should have been estimated as 1.4 and 3.2 mm for model 1 and 2, respectively. However, the numerical analysis yields maxima in differential images at 2 and 4 mm, respectively. It is quite clear from Fig. 2 that the area of the biggest difference between damaged and undamaged signals forms smooth lobes. The width of the shear wave reflection is approximately 0.5 mm for Model 1 and 1.7 mm for Model 2. This suggests that selecting the optimal source-receiver distance is more critical when the defect is closer to the plate surface.

In simulation data, large background signals could be removed from defect analysis simply by subtracting waveforms of damaged from undamaged samples. To suppress background wave modes in experimental data, an inverse filter was applied. Typically, such processing is used in imaging applications to deconvolve the known impulse response of an imaging transducer to improve axial resolution [41]. A number of techniques for robust inverse filtering have been proposed in the literature, including Wiener filter [41,42] and analysis of higher order signal statistics [43,44]. The algorithm used here performs deconvolution simply by dividing the signal spectrum by the spectrum of reference signals acquired over an undamaged area. The procedure is similar to Wiener filtering, but a predefined band-pass filter matching the spectrum of the acquired signal is used to suppress noise. The reference is unique for a given source-receiver distance and layout of the inspected structure.

In simulations, we used a thin Teflon layer and air-gap as defect models. We have shown that the arrival time of the shear wave does not depend on the defect material, although the reflection amplitude may change. Thus, taking into consideration both Model 1 and Model 2, alignment of the detection point to the maximum of the reflected shear wave arrival is, in our opinion, the most reasonable for practical in-field implementations. For Model 1, wave components formed by a combination of L and S waves and the transitions between them shown in Fig. 2 are much weaker than shear wave reflections. For Model 2, however, significant S-mode conversion at the defect was observed. This component also leads to effective damage imaging comparable to shear wave reflection.

It has been demonstrated that the lateral resolution decays with defect depth, decaying almost linearly with depth over the analyzed range. On the other hand, the elevation resolution does not depend on defect depth and simply equals half of the excitation beam width.

Inspecting structures with unknown or variable layer thickness using oblique propagating waves can be challenging since the source-receiver distance must be modified to be sensitive to reflections from varying depths. The procedure requires scanning a sample at various source-receiver distances and processing the full matrix, as is done for laser-induced phased arrays [45]. However, the depth of interest is known a priori for bonded metallic structures and, thus, the simple technique presented here is very well suited to practical applications in these structures.

The proposed approach has several additional advantages that make it particularly interesting for practical applications. It is all-optical and, hence, noncontact. The highly sensitive, fiber-optic Sagnac interferometer is very insensitive to environmental noise, which makes it well suited to industrial use. Finally, the compact size of the complete laser ultrasound system, consisting of a variable repetition rate pump laser and fiber-optic Sagnac interferometer, can be triggered from a position sensor, making it well-suited to robotic implementations.

6. Conclusions

We demonstrated a method for damage detection in multi-layered bonded plates using laser-generated ultrasound (LU). As longitudinal waves cannot be efficiently excited in metal plates in the non-ablative regime, we estimated defect location based on shear wave reflections. To improve the efficiency of shear wave excitation, a line-shaped laser source was used.

The resulting shear waves propagate at an oblique angle to the plate’s surface; therefore, the stand-off distance between source and sensing interferometer was assumed to maximize the amplitude of reflection. The distance was accurately estimated based on the wave propagation model using local interaction simulation approach (LISA).

To remove undesirable wave modes from measured responses, an inverse filter based on the reference signal from an undamaged plate was applied. This approach was successfully tested on a complex structure containing three epoxy-bonded aluminum plates, with artificial defects induced by Teflon inserts at both interfaces. The two defects were easily detected and their sizes in the in-plane dimensions were properly estimated. Finally, the greatest advantage of this method is that it leverages a compact, noncontact system that is easily applicable to the industrial environment.

The source-receiver distance for the specific approach presented here...
must be optimized for damage detection at a selected depth. Therefore, multiple scanning is required to inspect multi-layered structures. This problem could possibly be solved using a more complex pump beam shaped into multiple stripes spaced from the detector at designed distances.

The inverse filter requires keeping a constant source receiver distance. It could be challenging for complex-shaped components e.g. curved panels. To deal with this problem, an adaptive filter or bank of inverse filters will be studied in future work.

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**Declaration of Competing Interest**

The authors declare that there are no conflicts of interest.

**Appendix A. Numerical simulation**

Numerical simulations were carried out using a classic finite difference scheme coupled with the local interaction simulation approach (LISA). The procedure is briefly summarized below.

**Solution of the heat diffusion equation**

For a two-dimensional model in Cartesian coordinates, the heat equation is given as

\[ k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) = \frac{\rho c}{\Delta x} \frac{\partial T}{\partial t} - q \]  

(A1)

where \( k \) is the thermal conductivity, \( q \) the power density of the heat source, \( T \) is the temperature and \( x, y \) correspond to Cartesian coordinates.

Discretizing the structure into a point grid with spacing \( \Delta x, \Delta y \) and using the FD formalism (second order central difference in space and forward difference in time) yields the temperature in the grid point \((i,j)\) at the time step \( t+1 \)

\[ T_{i,j}^{t+1} - T_{i,j} = \frac{k}{\rho c \Delta t} \left( \frac{T_{i-1,j} - 2T_{i,j} + T_{i+1,j}}{\Delta x^2} + \frac{T_{i,j-1} - 2T_{i,j} + T_{i,j+1}}{\Delta y^2} + \frac{q_{i,j}}{k} \right) \]  

(A2)

where \( \Delta t \) denotes the time step.

An adiabatic boundary condition is introduced at the boundaries (i.e. first derivative of temperature with respect to the space variable in the direction normal to the insulated surface is equal to zero). This condition is fulfilled numerically using the mirror image concept [46].

**Solution of the wave equation**

To solve the wave equation, the two-dimensional Cartesian formulation developed by Delsanto [34] was followed while incorporating an additional term \( \beta \nabla T \) corresponding to the volumetric thermal expansion of the irradiated surface. This term provides the coupling between the heat and wave equations, while the backward coupling (temperature change due to introduced stress) is neglected.

Stress components

\[ \sigma_{xx} = (\lambda + 2\mu) \frac{\partial u}{\partial x} + \lambda \frac{\partial v}{\partial y} - \beta T \]  

(A3a)

\[ \sigma_{yy} = \lambda \frac{\partial u}{\partial x} + (\lambda + 2\mu) \frac{\partial v}{\partial y} - \beta T \]  

(A3b)

\[ \sigma_{xy} = \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \]  

(A3c)

Wave equation:

\[ \rho \ddot{u} = \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{yx}}{\partial y} \]  

(A4)

\[ \rho \ddot{v} = \frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} \]  

(A5)

where \( \lambda, \mu \) are the Lame' constants, \( \beta \) is the thermo-acoustic coupling constant and \( u, v \) are the unknown displacement components in the \( x \) and \( y \) directions, respectively.

Using matrix notation, equations (A4–5) are written as

\[ AW_{11} + BW_{22} + CW_{12} = \rho \ddot{W} + \beta \nabla T \]

where
Fig. A1. Schematic of two-dimensional LISA domain discretization into a grid point \((i, j)\) with constant material parameters \(\rho, \mu, \lambda\) of each cell. Adopted from Delsanto [34].

\[
A = \begin{bmatrix}
\lambda + 2\mu & 0 \\
0 & \mu
\end{bmatrix};
B = \begin{bmatrix}
\mu & 0 \\
0 & \lambda + 2\mu
\end{bmatrix};
C = \begin{bmatrix}
0 & \lambda + \mu \\
\lambda + \mu & 0
\end{bmatrix}; \\
W = \begin{bmatrix}
\ddot{u} \\
\ddot{v}
\end{bmatrix}
\]

and the index after a comma denotes the derivative with respect to a given quantity, for example, \(W_{12} = \frac{\partial^2 w}{\partial y^2}\). Note that this corresponds to the elastic wave propagation Eq. (2) presented in Section 2 for a two-dimensional case.

Discretizing the structure into a grid of square cells of extent \(\Delta x\) with constant material parameters for each cell, and using the FD formalism, yields the displacement in the grid point \((i, j)\) at time step \(t + 1\)

\[
W_{i,j+1}^{t+1} = 2W_{i,j-1} + \frac{(\Delta t)^2}{\rho\Delta x^2} \left[ A(W_{i+1,j} + W_{i,j-1} - 2W_{i,j}) + B(W_{i+1,j} + W_{i,j-1} - 2W_{i,j}) + C(W_{i+1,j+1} - W_{i-1,j+1} - W_{i+1,j-1} - W_{i-1,j-1}) - \beta \Delta x^2 \begin{bmatrix} T_{i+1,j+1} - T_{i+1,j} \\
T_{i+1,j+1} - T_{i+1,j}
\end{bmatrix} \right]
\]

where the single subscripts \(t, i, j\) were omitted for convenience.

Eq. (A4) is derived from the finite difference formalism. Next, following [34] the FD framework to evaluate wave displacement components is extended using local interaction simulation approach (LISA). LISA can analyze inhomogeneous media using the sharp interface framework. Material parameters are constant for each cell, but may differ from cell to cell (see Fig. A1). To obtain the iteration formula of cross points between cells, the second time derivatives of displacement vectors across four adjacent cells are required to converge towards a common value at the cells’ junction \(P\). This ensures that if the displacements are continuous at this nodal point for the two initial time instants, they remain continuous for all later times.

Since the derivation follows closely the one given in [34], only the final iteration formulae for displacement components \(u\) and \(v\) at the crosspoint \(P\) are presented below.

\[
u_{i,j+1}^{t+1} = 2u_{i,j} - u_{i,j-1} + \frac{(\Delta t)^2}{\rho_j} \left( \mu_j(4u_{i} - 6u_{j} + u_{j} - v_{i} - v_{j} - v_{i}) \\
+ \mu_j(4v_{i} - 6v_{j} + u_{i} + v_{i} - v_{j} - v_{i}) \\
+ \mu_j(4v_{i} - 6v_{j} + u_{i} - v_{i} - v_{j} - v_{i}) \\
- \lambda_j(2u - 2u_{j} + v - v_{i} + v_{j} - v_{i}) \\
- \lambda_j(2v - 2v_{j} - v + v_{j} + v_{j} - v_{i}) \\
- \lambda_j(2u - 2u_{i} - v + v_{j} + v_{j} - v_{i}) \\
- \lambda_j(2v - 2v_{i} - v + v_{j} + v_{j} - v_{i}) \right) / \Delta x^2 + \beta \Delta x^2 (T_i - T_{i+1,j});
\]
\[ v^{+1} = 2v - v^1 + \frac{\Delta t^2}{\rho k^2} \left( \mu_1 (u_1 - u - u_{1x} + u_{1y} - 6v + 2v_1 + 4v_2) \right) \]
\[ + \mu_2 (u - u_2 - u_1 - u_3 - 6v + 2v_3 + 2v_4). \]
\[ + \mu_3 (u - u_3 + u_2 - u_1 - 6v + 2v_3 + 4v_4). \]
\[ + \mu_4 (u - u_4 - u + u_{1x} - u_{1y} + u_{2x} - u_{2y} + 2v_2 - 2v_4). \]
\[ + \mu_5 (u - u_5 - u_3 - u_1 + 2v_2 - 2v_4). \]
\[ + \mu_6 (u - u_6 + u_1 - u_3 + u_{2x} - u_{2y} + 2v_2 - 2v_4). \]
\[ + \lambda_1 (u - u_1 - u_{1x} + u_{1y} - 2v + 2v_1). \]
\[ + \lambda_2 (u - u_2 - u_{1x} + u_{1y} - 2v + 2v_1). \]
\[ + \lambda_3 (u - u_{1x} - u_{1y} + 2v - 2v_1). \]
\[ + \lambda_4 (u - u_{1x} - u_{1y} + 2v - 2v_1) / \Delta x^2 + \beta \Delta x^2 (T_0 - T) \]

where \( \rho_k = \frac{4}{\sum_{k=1}^{4}} \rho_k \)

At the boundaries of the model, an additional single layer of material with parameters equal to zero is modeled to fulfill the boundary condition of the free surface.

### Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:10.1016/j.phoac.2020.100226.

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