

Adhesive bond thickness inversion using through transmission data

Arno Volker, Patrick Jansen
Royal Netherlands Aerospace Centre,
Marknesse, 8316 PR, The Netherlands
+31 6 20541175
arno.volker@nlr.nl

Abstract

Bonded metal panels are frequently used in aircraft structures. Non-destructive inspections are performed to ensure the integrity of these panels. A commonly applied method is through transmission ultrasonic inspection. Due to the layered structure of these panels, the transmission response is strongly frequency dependent and consists of a series of resonance peaks. Even a small thickness variation in the bondline causes a strong imprint in C-scan images. This imprint is generally considered as an undesired output, complicating the interpretation of the inspection. Bondline thickness variations may affect the mechanical properties of the panel. As the imprint contains information about the actual thickness of each individual bondline, this data could be utilized to assess the mechanical properties of the bonded structure.

This resonance pattern can be calculated using a simple 1D-transmission model. An inversion scheme has been developed to determine the local bondline thickness of each individual bondline from transmission data. The uniqueness of the solution is studied for panels with three bondlines. The approach has been evaluated on aluminium bonded panels with one and three bondlines. Using the estimated bondline thicknesses and the thickness of the individual aluminium panels the total panel thickness can be calculated, which shows good agreement with reference measurements.

1. Introduction

Aluminium bonded panels are commonly used in aircraft structures. In general, the lay-up consists of aluminium panels with varying thickness bonded with an adhesive. To ensure the integrity of newly produced panels, an ultrasonic inspection is performed by transmitting ultrasound through the panel. Anomalies in the panel, show-up as a local drop of the transmission signal amplitude. During the production process, adhesive thickness variations may occur. These thickness variations potentially affect the mechanical properties of the panel. Moreover, these thickness variations have a strong influence of the amplitude of the transmitted wave. This complicates the interpretation of the inspection result.

As the transmission signal contains a characteristic fingerprint of the panel lay-up, it is interesting to evaluate if this bondline thickness can be extracted from the measurement.

2. Transmission response

The transmission response can be calculated using a simple 1D transmission line model, taking into account the interface reflection/transmission coefficients and the acoustic properties of the individual layers. A 4 MHz transducer with 80% bandwidth at -20 dB has been simulated. The response is characterized by standing-wave resonances, leading to a characteristic set of resonance peaks. An example is shown in Figure 1 for metal bonded panels with one and three bondlayers. The total thickness of these panels equals 3.35 and 6.45 mm respectively. With increasing thickness, more pronounced peaks appear in the frequency spectrum.

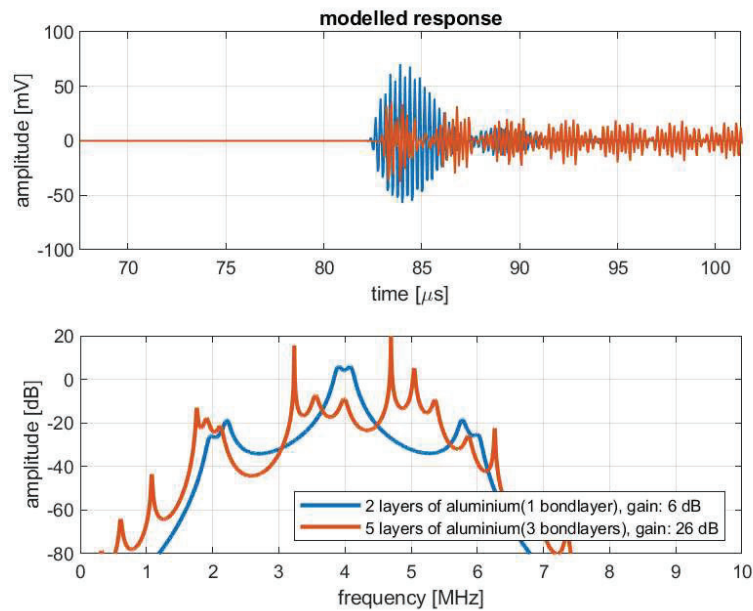


Figure 1 Example of synthetic responses for aluminium panels with one and three bondlayers. The total thickness of these panels equals 3.35 and 6.45 mm respectively. With increasing thickness, more pronounced peaks appear in the frequency spectrum.

The phase spectrum of the transmission response consists of series extrema, with an alternative phase between zero and π . This makes it easy to consistently trace modes in case of varying bondline thickness. Figure 2 shows how the various frequency peaks shift for a varying bondlayer thickness. In this case the lay-up consist of two, 1.6 mm thick aluminium panels with one bondline in between these sheets. The compressional wave velocity in the aluminium is 6380 m/s and the density equals 2780 kg/m³. The bondline acoustic properties⁽¹⁾ are 2433 m/s and the density equals 1214 m/s. The nominal bondline thickness is supposed to be 150 μm . In this example the bondline thickness is varied from 50 to 300 μm . An ultrasonic C-scan inspection would typically be performed at 5 MHz. From Figure 2 it become clear that several modes around this frequency vary significantly with increase bondline thickness. The amplitude of each mode remains fairly constant, i.e., within 1 dB.

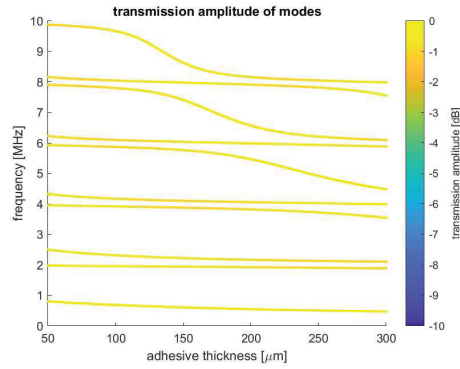


Figure 2 Transmission response of two aluminium sheets with a single bondline.

The response of a multi-layer stack becomes significantly more complicated. The lay-up is shown in Figure 3. The total thickness is 6.45 mm.

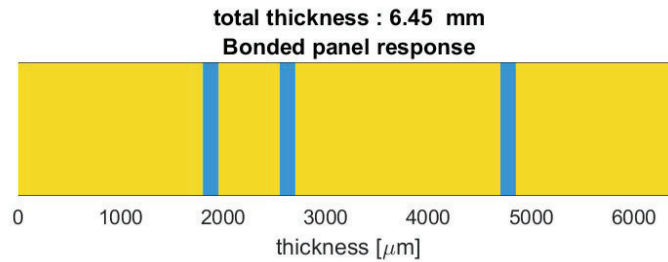


Figure 3 Lay-up of three bondline case, the bondlines are indicated in blue and the aluminium layers are indicated in yellow.

Figure 4 shows the response of a five layer stack of aluminium sheets with thicknesses varying between 0.6 and 2 mm. The nominal adhesive thickness is 150 μm , in each plot, only one bondline thickness is varied. From this plot it is clear that many more modes appear compared to the single bondline case. Moreover modes do have significantly different amplitudes and the amplitude changes much more as function of bondline thickness. Only at low frequencies (below 1 MHz), the mode amplitude remains fairly constant. However, the sensitivity for detecting particular defects is too low below 1 MHz.

The black line in Figure 4a tot c indicates the nominal bondline thickness. The transmission responses are obviously the same. However, the mode pattern changes differently for the three bondlines. This suggests that the pattern is unique, which is required to be able to determine the individual bondline thickness. This will be investigated in more detail after explanation of the inversion scheme.

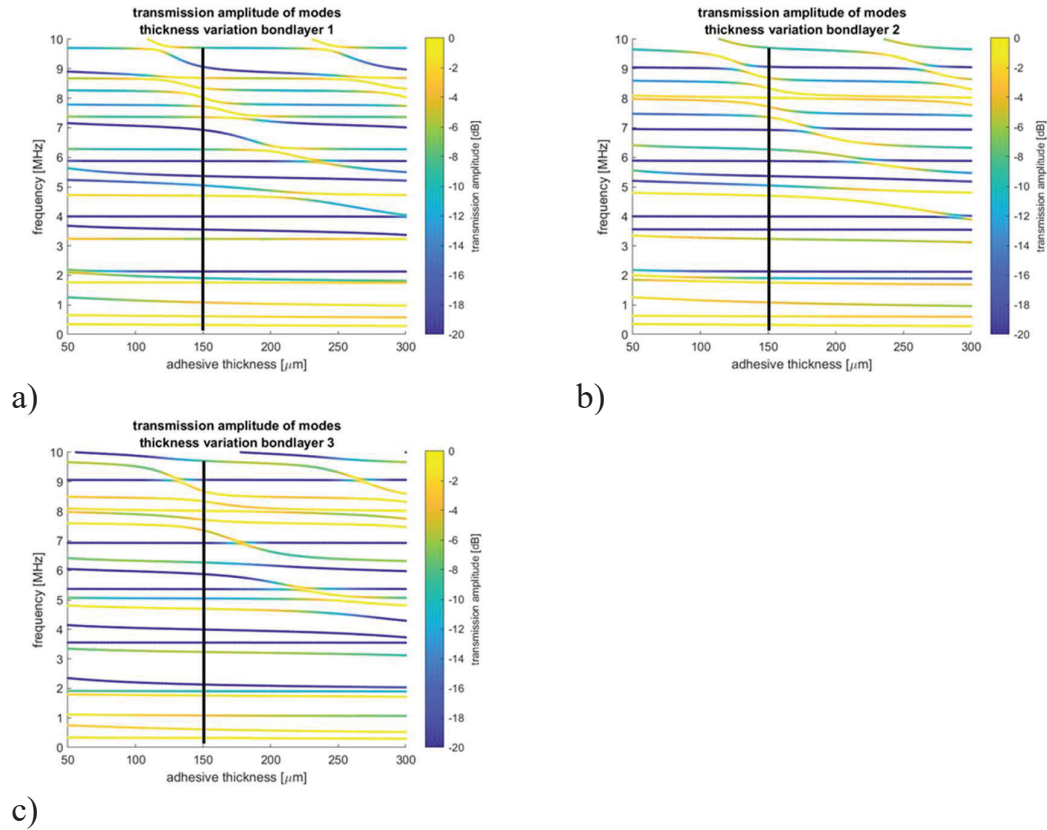


Figure 4 Transmission response of five aluminium sheets with a three bondlines, a) thickness variation in the first bondline, b) thickness variation in the second bondline and c) thickness variation in the third bondline. For a nominal thickness of 150 μm (black line), the three responses are the same.

3. Inversion approach

3.1 Inversion scheme

An inversion scheme has been implemented to determine the thickness of each individual bondlayer. In this approach, the thickness and acoustic properties of the aluminium layers are assumed to be known. The acoustic properties of the adhesive is also assumed to be known. The thickness of each bondlayer is varied with fairly coarse steps for computational efficiency. The frequency of each specific mode is obtained as a function of the individual bondline thickness. This yields an N-dimensional cube (ND). If required, the ND-cube can be interpolated easily because the frequency varies very smoothly as function of all thickness parameters. As can be seen from Figure 4, there are several instances where two modes are very close increasing the risk of inconsistent mode tracing. Inconsistencies in the mode tracing would degrade the inversion and should therefore be avoided. As explained before, mode tracing from the transmission response is very straightforward and robust using the phase extrema. Inversion of the C-scan data works on a trace by trace basis. The measured transmission signal is Fourier transformed. The measured signal amplitude at the frequency from the ND-cube is extracted for each mode. The amplitudes for all modes are combined

using the L1-norm. The combination of bondline thicknesses that maximizes the norm yields the most likely solution.

3.2 Non-uniqueness analysis

To evaluate the non-uniqueness of this inversion problem, a simulation study is performed for the three bondlayer case. In this simulation, the thickness of each bondlayer is varied randomly. The resonance frequencies are calculated and each frequency is randomly perturbed using gaussian noise. The standard deviation of the perturbation is varied from 10 kHz to 100 kHz. Then the bondline thickness is determined by comparing the set of resonance frequencies with a precalculated resonance frequency cube. In total a 1000 simulations are performed. From these simulations, histograms are computed showing the error for each bondline. The results are shown in Figure 5, for a standard deviation of 10, 20 50 and 100 kHz respectively. Up to 50 kHz, the standard deviation remains very small. At 100 kHz, the standard deviation of the bondline thickness increases, mainly caused by a limited number of outliers. These outliers occur when the wrong optimum is selected by the inversion scheme. In a real measurement, there are several sources of uncertainty in the peak frequency, the most important ones are the frequency resolution and the bandwidth of the transducer. Overall this approach seems quite robust.

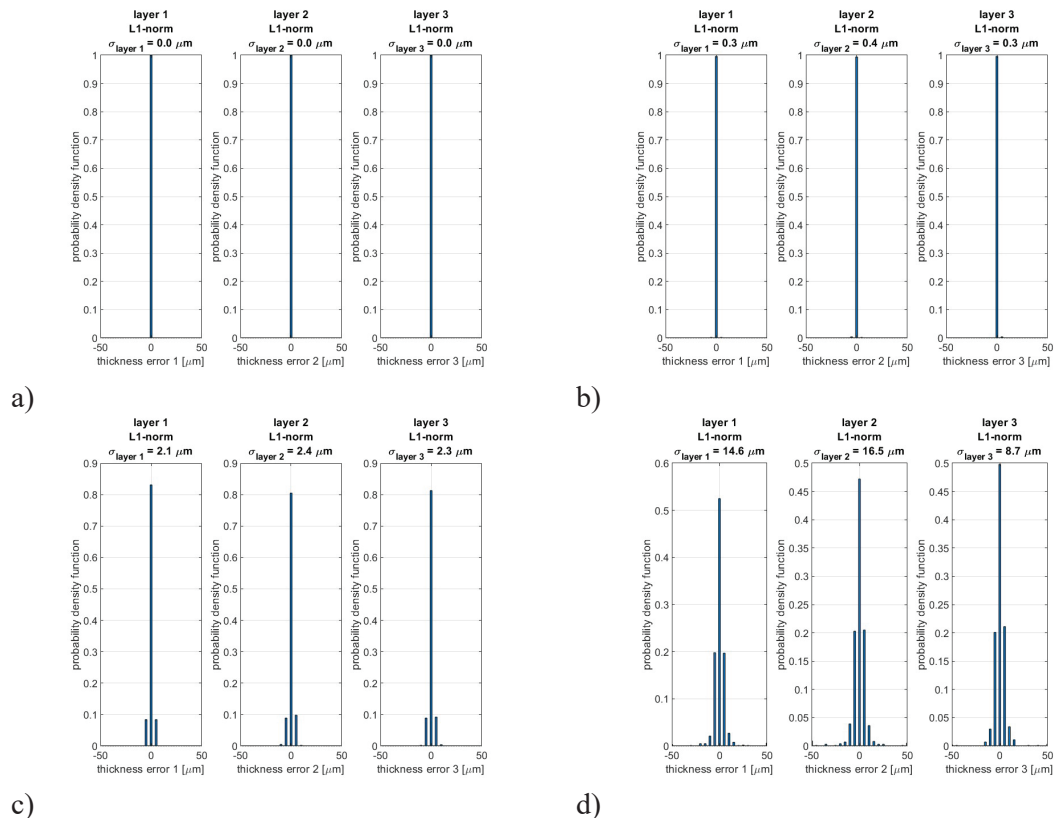


Figure 5 Non-uniqueness analysis of the inversion problem, the resonance frequencies are randomly perturbed to evaluate the error in bondline thickness estimation. The standard deviation of the perturbation equals a) 10 kHz, b) 20kHz, c) 50 kHz and d) 100 kHz.

4. Experimental results

Bonded panels with one and three bondlines have been produced to evaluate this method experimentally. Through transmission inspections are performed with 5 and 10 MHz transducers using a conventional squirter system (see Figure 6a). A 3D scanner (Zeiss, Atos 5) was used to measure the thickness of the panels, by placing them on a rotation table (see Figure 6b). By rotating the sample, a thickness map is obtained.

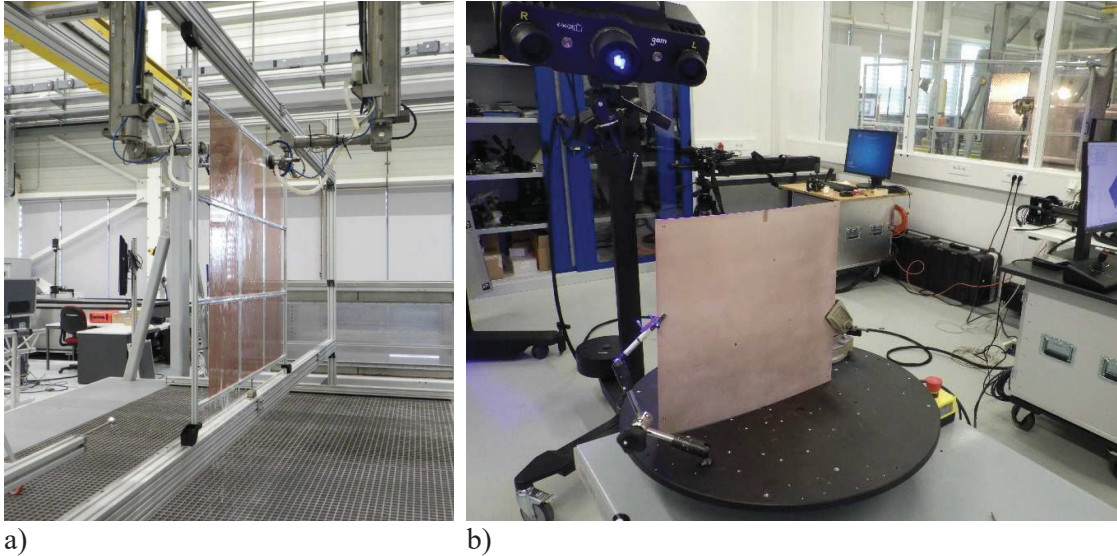


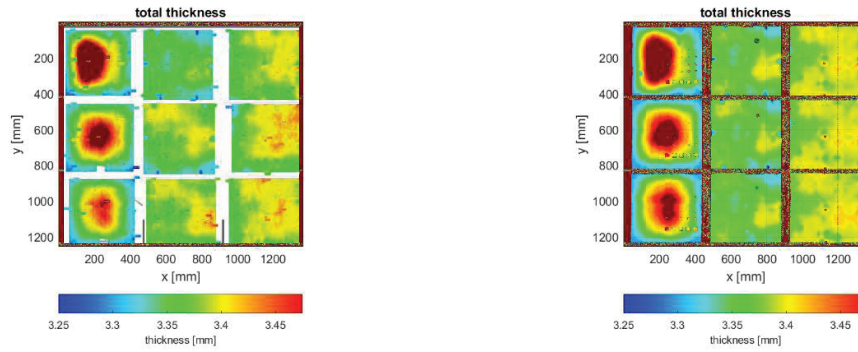
Figure 6 Measurement set-up used to inspect the bondline samples, a) squirter system to perform through transmission measurement, b) 3D scanner to measure the thickness of the samples.

4.1 Single bondlayer

C-scan measurements have been processed to obtain the local bondline thickness. In order to validate the results, the total thickness of the panel is calculated using 1.6 mm for both aluminium sheets. The thickness map obtained by the 3D scanner is shown in Figure 7a. This image shows a matrix for 3 x 3 panels, which were individually produced. The panels shown in the first column from the left hand side, where produced in an autoclave, while the other panels were produced in a heated press. This explains the difference in thickness.

The thickness map from the inversion scheme is shown in Figure 7b. Each trace is processed individually. The inversion result produces a laterally coherent image, which is another confirmation that the inversion is well-conditioned. Comparison of the two thickness maps shows that the results match quite well, differences are typically in the order of 30 μm . Both methods contain measurement errors. Alignment markers are used to co-registrate different 3D scanner images. This makes it possible to create a thickness map. It is estimated that thickness measurement error of the 3D scanner is in the order of 20 μm .

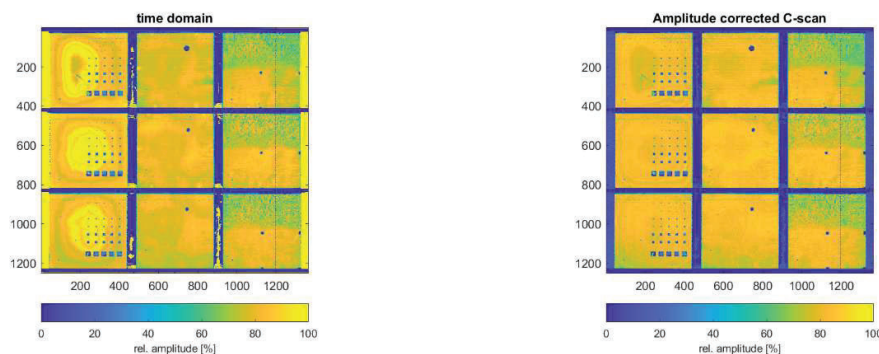
Important error sources in the inversion method are uncertainties in material parameters, the spectral resolution and the bandwidth of the ultrasonic transducer. The uncertainty estimate from the inversion is in the same range as the 3D scanner, i.e., 20 μm .



a) b)
Figure 7 Thickness maps obtained by a) 3D scanner and b) inversion of through transmission measurements.

Figure 8a shows the original C-scan for the nine panels. The maximum amplitude of the transmission signal is shown in this C-scan image. In the first column of three panels seen from the lefthand side, artificial defects are inserted with different sizes. The second column contains panels where intentionally contamination was applied on bond surfaces to produce poorly bonded panels (kissing bonds). As can be seen from the C-scan, this produced one disbond. Apart from this disbond, no anomalies are observed. The third column contains panels with porosity in the top half. Due to the production process of the panels with the artificial defects, bondline thickness variations occurred. The bondline thickness variations leave a significant imprint on a C-scan image. Using the obtained bondline thickness from the inversion, it now becomes possible to apply an amplitude correction to remove/minimize the imprint. After applying an amplitude correction based on the estimated bondline thickness a new C-scan image is obtained (see Figure 8b).

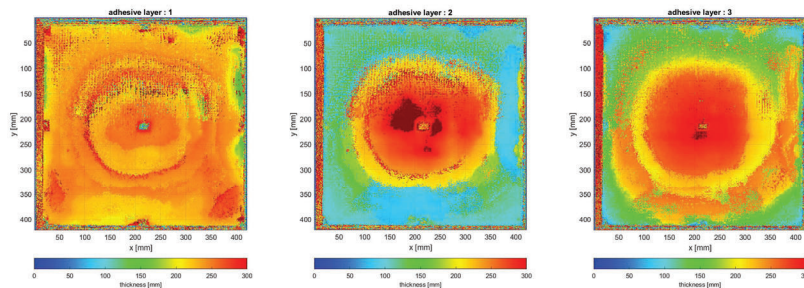
The defects remain clearly visible in the C-scan images, but the influence of thickness variations is almost removed completely in all nine panels.



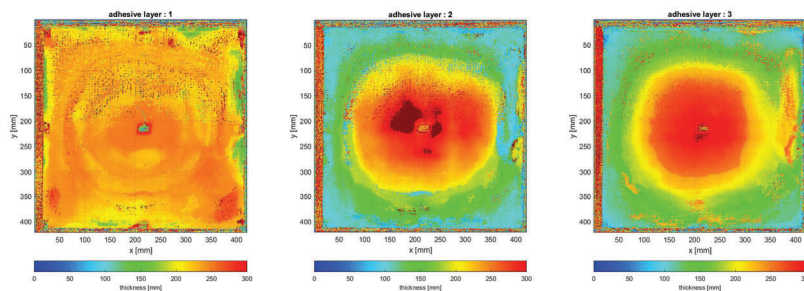
a) b)
Figure 8 C-scan images of the nine different panels, a) original C-scan and b) C-scan after applying an amplitude correction based on the estimated thickness.

4.2 Triple bondlayer

The next example is a stack of five aluminium panels with three bondlayers, the nominal lay-up is as indicated in Figure 3. The top half of the panel contains porosity in one bondlayer. During the production, spacers were applied in the first bondline to ensure a more uniform thickness. Through transmission measurements were performed using either a set of 5 MHz transducers or a set of 10 MHz transducers. The bandwidth of these transducers is typically 70% at -6 dB. Two inversions are performed, one using the 5 MHz data only and one using both measurements. In the latter case, the measured signals were simply summed together after compensating from small lateral alignment differences between the two datasets. The bond thickness inversion results are shown in Figure 9. As expected, the first bondlayer shows a much more uniform thickness because of the used of spacers. Bondlayers 2 and 3 do show significant thickness variations. The porosity in the upper half of the panel has some influence on the measured thickness, but the variation in thickness remains clearly visible. Due to bandwidth limitations of the transducers, a limited number of resonance peaks is present. This does have some adverse effect on the thickness measurement as can be seen from comparing Figure 9a (5 MHz only) to Figure 9b (5 and 10 MHz). Combining measurement from the 5 and 10 MHz transducers produces a more consistent thickness map.



a)

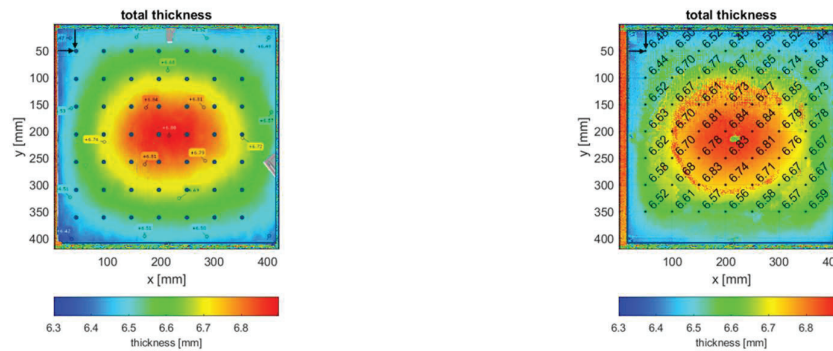


b)

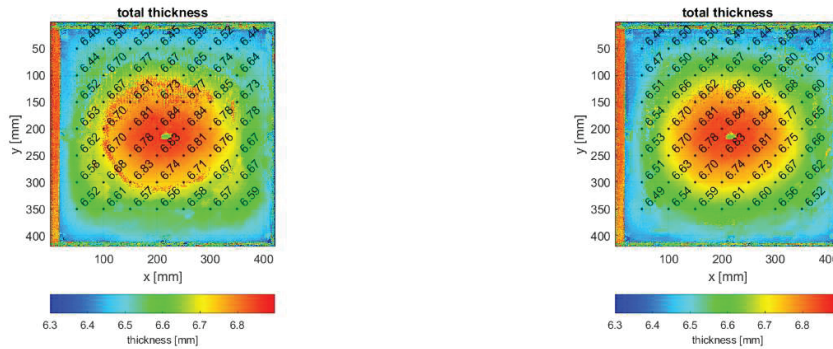
Figure 9 Individual bond thickness maps using, a) only data from 5 MHz transducers, b) combining data from 5 and 10 MHz transducers. Due to the use for spacers, bondlayer 1 has a much more uniform thickness, compared to the two other bondlines.

It is not possible to validate the individual bond thickness readings without destroying the sample. Instead the total thickness is calculated assuming a uniform thickness of the individual aluminium panels. The total thickness is compared to the measurement from the 3D-scanner. Figure 10 shows a comparison of the 3D scanner result with the thickness map obtained from the 5 MHz transduce only. The markers in the 3D scanner results match with the position of the thickness values displayed in the inversion result. The colormaps in both images are identical for easy comparison. The results match quite well.

Figure 11 shows a comparison of the thickness maps obtained with only the 5 MHz data and the map for the combined dataset. This image clearly improves, but differences are typically less than 50 μm . The combined frequency result also matches better with the 3D scanner result.



a) b)
Figure 10 Comparison of thickness maps for the three bondline sample produced using a) the 3D scanner and b) using the developed bondline thickness estimation scheme using only the data from the 5 MHz transducer.



a) b)
Figure 11 Comparison of thickness maps for the three bondline sample produced using the inversion scheme, using a) only data from the 5 MHz transducer and b) the combined data from the 5 and 10 MHz transducer.

5. Conclusions and discussion

A bondline thickness estimation method has been developed that is capable of estimating the individual bond thickness from ultrasonic transmission measurements. The approach is quite robust and produces spatially coherent thickness maps, although signals are processed individually. The approach has been demonstrated on single and triple bondline panels. The method is also expected to work for panels with even more bondlines. The approach relies on matching a series of resonance peaks with a forward model. The forward model requires the acoustic properties of the individual layers.

The total thickness determines the number of resonance peaks within the signal bandwidth, the more peaks are available, the better the method works. To expand the signal bandwidth, it is possible to sum signals from different transducers.

There is one important constraint for multiple bondline panels. In case all the aluminium sheets in one stack are equally thick, it is not possible to determine in which bondline the thickness variation occurs. For example in a panel with five equally thick sheets it is not possible to identify whether the thickness variation occurs in bondlayer one or three, because of the symmetry. It is however possible to successfully estimate the thickness variations in bondlayer two.

Using the estimated bondline thickness, it is possible remove/reduce the imprint that thickness variation have on the C-scan. This makes interpretation of C-scan images easier, reducing inspection lead-times.

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Reference

1. Jasiūnienė, E., Yilmaz, B., Smagulova, D., Bhat, G. A., Cicėnas, V., Žukauskas, E., Mažeika, L., & MDPI AG leidėjas. (2022). Non-destructive evaluation of the quality of adhesive joints using ultrasound, X-ray, and feature-based data fusion. Applied Sciences. <https://doi.org/10.3390/app122412930>