Simultaneous Determination of Thickness and Sound Velocity in Layered Structures

Sebastian KÜMMRITZ, Mario WOLF, Elfgard KÜHNICKE

Solid-State Electronics Laboratory, Technische Universität Dresden; Dresden, Germany; Phone: +49 351 463 35367; e-mail: sebastian.kuemmritz@tu-dresden.de

Abstract
A novel method for simultaneous determination of thickness and sound velocity by the use of ultrasound is presented. In order to get additional information beside the time of flight, the focal point is varied and the amplitudes of the echo signals are evaluated. The amplitude of each echo is highest when the focus is positioned on the considered interface. The position of the focal point is varied by synthetic focusing with an annular array, while the probe is located at a fixed position. The delay times are determined by a geometrical sound propagation model which takes reflection and refraction effects into account. The two information, delay times for the maximal echo amplitude and time of flight, allow the simultaneous determination of sound velocity and thickness in each layer of multi-layered structures. An additional correction of the focal point by sound field simulations results in an accuracy of more than 98% for a two-layered system.

Keywords: Ultrasound Testing, Phased Array, Annular-Array, Material Characterization

1. Introduction

Neither thickness nor sound velocity of a plate can be determined via simple Time of Flight (ToF) measurements, when both quantities are unknown. In the field of non-destructive testing the material parameter speed of sound is presumed as known. So the position of defects can be determined with the measured ToF. In material characterization the thickness of a plate is measured for instance mechanical. Then, the speed of sound is determined. If a multi-layer-structure is tested (Figure 1), it is necessary to determine both quantities simultaneously to get information about the thicknesses and the material of the different layers.

Hsu [1] discussed a method for the simultaneous measurement of thickness and sound velocity for a single-layer specimen with coplanar surfaces. For that method, the specimen has to be placed between two probes with a known distance.

Speed of sound and thickness of each layer of a multi-layered specimen can also be determined with tomographic methods [2], however, combined with high effort for measurement and evaluation, because a large number of probes is necessary.
Another method is the determination of sound velocity and thickness via measuring two quantities: ToF and focal position. This is possible since focal position depends on the parameters of the probe and also on the speed of sound in the specimen.

Based on this idea, in [3] the thickness of a one-layered specimen is determined without knowledge of its sound velocity. For this purpose a strong focusing probe is shifted to locate the focal point first at the surface and then at the back wall of the specimen. Probe displacement for focusing on surface and back wall as well as ToF for the sound propagation path between the interfaces are measured to determine the thickness and speed of sound of the specimen simultaneously. With this method, however, the measurement uncertainty is partially higher than 10%.

2. Idea

The main idea is to use, beside the ToF, the focal position to determine speed of sound and thickness simultaneously. The echo amplitude depends on the position of the specimen in the sound field of the probe (see Figure 2). The basic assumption is that the echo is highest, if the focal point is located on the surface (blue curves) or on the back wall (red curves). The echo amplitudes of surface and back wall reflection are recorded while the probe is shifted down in z-direction. The probe displacement between the positions of the maximum of surface and back wall as well as the ToF allows determining the thickness and the sound velocity.

![Figure 2: The amplitude of each echo depends on the position of the considered interface in the sound field of the probe. Is the focal point on an interface, the appropriate echo becomes maximal.](image)

So far, this approach does not differ from [3]. In this contribution instead of the probe only the focal position is varied. This can be realized with a delayed excitation of the segments of an annular array. The main advantage of annular arrays in contrast to linear or matrix arrays is the small number of segments needed for focusing. This minimizes technical effort. The used probe consists of six ring segments with a centre frequency of about 7 MHz. The inner \( r_1 \) and outer radii \( r_a \) of each segment are presented in Table 1. The structure with numbered segments is shown in Figure 3 a).

<table>
<thead>
<tr>
<th>Elementnummer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
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<td>( r_1 ) [mm]</td>
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<td>3,51</td>
<td>4,36</td>
<td>5,10</td>
<td>5,77</td>
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<tr>
<td>( r_a ) [mm]</td>
<td>2,24</td>
<td>3,31</td>
<td>4,16</td>
<td>4,90</td>
<td>5,57</td>
<td>6,58</td>
</tr>
</tbody>
</table>

Table 1: Inner and outer radii of the used probe

To vary the focal position, synthetic focusing was used. For that purpose, any segment was excited separately with electrical pulses of about 100 V and a duration of 4 ns, while all
segments receive the echo signals. This results in 36 different emitting-receiving-combinations. The time signals of each emitting-receiving-combination \( \text{sig}_{E,R}(t) \) (E \( \triangleq \) emitter; R \( \triangleq \) receiver) are time shifted with \( \Delta t_{E,R} \):

\[
\text{sig}_{E,R} = \text{sig}_{E,R}(t - \Delta t_{E,R}),
\]

which can be seen in Figure 3 b) and c). Afterwards, the time shifted signals are superposed:

\[
\text{sig}_{\text{sum}} = \sum_E \sum_R \text{sig}_{E,R}.
\]

The aim is to find that set of delay times \( \Delta t_{E,R}(c, z) \) where the amplitude of the sum signal \( \text{sig}_{\text{sum}} \) becomes maximal (N stands for the number of used ring segments). The delay time matrix is a function of sound velocity and thickness of the respective layer. The ToF

\[
\text{ToF}(c, z) = \frac{2z}{c}
\]

gives the second measure to determine speed of sound and thickness.

![Figure 3: a) Probe design with segment numeration- b) time signal of the configuration emitter: 3, receiver: 4 - c) time shifted signal of the configuration emitter: 3, receiver: 4](image.png)
For the evaluation of the sum signal (Figure 4 blue graph) the amplitude can be used. However, it has been shown that the area below the envelope (Figure 4 - red hatching), as a quantity for the signal energy, is more stable for evaluation. When the denotation signal energy is referred in the following, the reference is, in fact, to the area below the envelope.

Figure 4: time signal (blue graph), envelope (red graph) and area below the envelope (red hatching)

3. Approach

3.1 Single Layer

Initially, a single-layered structure will be discussed. This corresponds to a distance measurement with unknown speed of sound between probe and reflector. To determine the position of the interface, the focal position is varied. For calculating the delay times to a specific focal point, the sound propagation paths $d_{E,R}$ from each and any emitting segment to the focal position and back to each and every receiving segment are needed (Figure 5).

The goal is to focus on the interface between medium 1 and medium 2, which is at a distance $z_1$. Since the actual distance is not known, it will be focused on an assumed interface at a distance of $z_1'$. Afterwards, $z_1'$ will be varied until the sum signal becomes maximal. Conventionally, for focusing a point on the acoustic axis is chosen (Figure 5, red point). In the event that emitter and receiver are the same, the angle of incident and the angle of reflection are equal (Figure 5, red point, continuous lines). If emitter and receiver are different, these angles are unequal (Figure 5, red point, dotted lines). The aim is to maximize the sum signal. Thereby, it is more reasonable to use the sound propagation paths, where angle of incident and the angle of reflection are equal (Figure 5, green point, dashed lines). That case is named focusing on a plane. The resulting sound propagation paths can be calculated with

$$d_{E,R} = 2 \cdot \sqrt{z_1^2 + \left(\frac{r_E-r_R}{2}\right)^2}.$$  \hspace{1cm} (5)

$r_E$ as well as $r_R$ symbolize the radii of the centre of area

$$r_{E,R} = \frac{1}{A} \int_{r_i}^{r_a} r \cdot (2\pi r) \, dr = \frac{2\pi}{3A} \left(r_a^3 - r_i^3\right)$$  \hspace{1cm} (6)

for all ring segments (the centre of area of the central element is zero) and $A$ the area of the respective probe segment. The required sound propagation times are determined by dividing the sound propagation paths by the sound velocity $c_1'$ of medium 1, which is arbitrarily chosen. The time delays for each emitter-receiver-configuration result from
\[ T_{E,R} = \frac{d_{ER}}{c_1'} - \frac{d_{11}}{c_1''}, \]  

(7)

For all combinations without the central segment two different sound travel paths exist (see Figure 6 for the example emitter 3 - receiver 4; the corresponding signal can be seen in Figure 3b)). If the signals for all emitting-receiving-combinations are time shifted with the correct time lags, the second signal components interfere with each other constructively and the sum signal becomes maximal.

Below, the simultaneous determination of thickness and sound velocity is demonstrated. A plane reflector in water \((c_1 = 1482 \text{ m/s})\) is located in a distance of \(z_1 = 20 \text{ mm}\) in front of the probe. In a first step a sound velocity of about \(c_1' = 1000 \text{ m/s}\) is assumed. The necessary time lags are determined for each emitting-receiving-configuration for focus positions \(z_1'\) between 15 and 45 mm. Afterwards, the signal energy of the sum signal is determined for each focal position. This leads to a function of signal energy vs. focus position (blue curve in Figure 7). It can be seen, that this function becomes maximal for a reflector distance of about 30.1 mm. This means, if the water had a sound velocity of about 1000 m/s, the interface would be in a distance of about 30.1 mm.
Since the speed of sound is not known, the algorithm has to be repeated for different (assumed) sound velocities. As can be seen from Figure 7, for each assumed speed of sound another corresponding distance is determined. The case \( c_1 = 1482 \text{ m/s} \) (red dashed lines in Figure 7) is only shown to demonstrate, that the model provides the actual reflector distance if the chosen sound velocity is correct.

The so determined reflector distances as a function of (assumed) speed of sound can be seen in Figure 8 (red points) for ten different sound velocities. The ansatz for the course of this function is an hyperbola. Based on the pairs of sound velocity and distance, this hyperbola is fitted (blue curve).

In order to determine the correct pair of sound velocity and reflector distance, a further quantity is required. The measured ToF can be applied here. The reflector distance can be expressed as a function of sound velocity and ToF (black curve). The intersection point of
these two curves identifies the correct sound velocity of $c_1 = 1487 \text{ m/s}$ (and a corresponding reflector distance of 19.97 mm). Hence, the relative deviation of the presented method is 0.15%.

Further examinations for the first layer are missing in this contribution, because a methodical examination of different media and various reflector distances was already done in [4]. It was concluded that a good probe adjustment results in a measurement accuracy of more than 99% if inclination of the probe will be avoided.

### 3.2 Two-Layer

After speed of sound $c_1$ and thickness $z_1$ of the first layer are determined, the method is applied to a second one. The difference to the single-layer configuration is, that the refraction of sound at the interface between medium 1 and medium 2 for the geometric determination of delay times (Figure 9) has to be considered.

In order to calculate the sound propagation paths, the points $y_E$ and $y_R$ are required, where the sound passes the interface between medium 1 and medium 2. Therewith the sound propagation times can be calculated with

$$
T_{ER} = 2 \cdot \sqrt{\frac{(r_{ER} - r_{ER})^2 + z_1^2}{c_1}} + 2 \cdot \sqrt{\frac{(r_{ER} - r_{ER})^2 + z_2^2}{c_2}}
$$

(8)

To determine $y_E$ or $y_R$ FERMATS principle can be used:

$$
\frac{dT_{ER}(y_{ER})}{dy_{ER}} = 0.
$$

(9)

### 3.3 Correction of the geometric model with sound field simulations

In the way described above a sound velocity of $c = 6990 \text{ m/s}$ (and a thickness of 11.71 mm) was determined for a 9.91 mm steel plate ($c = 5913 \text{ m/s}$) after a water delay line of 20 mm. This means a deviation of more than 15.4%. Sound field simulations can help to minimize this error.

The sound field of each segment of the probe is calculated for the measurement set-up by a half-analytical method based on time-harmonic GREEN's functions [6]. With Equation (8),
the delay times for focusing on 10 mm in steel \((c = 5920 \text{ m/s})\) after a 20 mm water delay line \((c = 1500 \text{ m/s})\) are calculated. With these delay times the sound fields of the single segments are phase-shifted and superimposed. The resulting sound field is shown in Figure 10. It can be seen, that the actual focus differs from the geometrically adjusted.

Figure 10: Sound field in steel \((c = 5920 \text{ m/s})\) for geometric focusing according to Equation (8) on 10 mm after a 20 mm water delay line \((c = 1500 \text{ m/s})\)

Figure 11 shows the correct focal point as a function of the geometrically adjusted focal point for focusing between 21 and 50 mm in steel after a water delay line of 20 mm. This function allows a correction of the focal point.

Figure 11: Real focal point as a function of adjusted focal point for steel \((c = 5920 \text{ m/s})\)

4. Results and Discussion

For a statistical evaluation a mechanical scan of the specimen was performed. The probe position varied over a region of 10x10 points with a resolution of 100 µm in the x-y-plane at a fixed z-position. All evaluations where done for the 100 measurement positions. In Table 2 and Table 3 the values for the simultaneous evaluations as well as the sound velocity for the conventional measurement are presented in the format: mean value ± variance. For the conventional measurement the ToF was measured and the sound velocity was determined with Equation (4) (the thickness was determined with a caliper gauge).

4.1 Steel

The conventionally determined sound velocities for the different steel plates are in the range of 5908 up to 5961 m/s (see Table 2). Therefore, they are within the usually given standard of 5890 up to 5960 m/s depending on alloy and heat treatment [7]. The measurement uncertainty is mainly caused by the thickness measurement, which has an accuracy of about \(\Delta d = 0.03 \text{ mm}\). The accuracy of the Time of Flight measurement is \(\Delta ToF = 8 \text{ ns}\). These
accuracies lead to a tolerance range for the sound velocity determined by the error propagation law

$$\Delta c = \frac{2}{T_o F} \Delta d + \frac{d}{T_o F^2} \Delta T_o F,$$

of up to ± 61 m/s.

### Table 2: Results steel

<table>
<thead>
<tr>
<th>d (default) [mm]</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
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<td><strong>Conventional measurement</strong> (d with caliper gauge, c with Equation (4))</td>
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</tr>
<tr>
<td>d [mm]</td>
<td>4.09 ± 0.03</td>
<td>5.94 ± 0.06</td>
<td>7.94 ± 0.03</td>
<td>9.91 ± 0.03</td>
<td>13.97 ± 0.03</td>
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<tr>
<td>c [m/s]</td>
<td>5942 ± 9</td>
<td>5940 ± 0</td>
<td>5961 ± 0</td>
<td>5913 ± 1</td>
<td>5908 ± 4</td>
</tr>
<tr>
<td>Δc [m/s]</td>
<td>61</td>
<td>42</td>
<td>31</td>
<td>25</td>
<td>18</td>
</tr>
<tr>
<td><strong>Simultaneous measurement without focus correction</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d [mm]</td>
<td>4.42 ± 0.02</td>
<td>6.42 ± 0.02</td>
<td>8.95 ± 0.03</td>
<td>11.71 ± 0.04</td>
<td>17.54 ± 0.09</td>
</tr>
<tr>
<td>c [m/s]</td>
<td>6418 ± 24</td>
<td>6415 ± 19</td>
<td>6716 ± 21</td>
<td>6990 ± 25</td>
<td>7420 ± 37</td>
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<tr>
<td><strong>Simultaneous measurement with focus correction</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d [mm]</td>
<td>4.02 ± 0.04</td>
<td>6.00 ± 0.04</td>
<td>8.05 ± 0.05</td>
<td>10.07 ± 0.07</td>
<td>13.89 ± 0.03</td>
</tr>
<tr>
<td>c [m/s]</td>
<td>5843 ± 18</td>
<td>6004 ± 22</td>
<td>6047 ± 22</td>
<td>6009 ± 12</td>
<td>5877 ± 16</td>
</tr>
</tbody>
</table>

The conventional and simultaneous values of sound velocity of the same measuring procedure are compared. As can be seen in Table 2, without focus correction the error for the determined sound velocities rises up to 20 %. With focus correction the simultaneous determined sound velocity differs from the conventional between 0.5 to 1.7 %.

### Table 3: Results aluminum

<table>
<thead>
<tr>
<th>d (default) [mm]</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional measurement</strong> (d with caliper gauge, c with Equation (4))</td>
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</tr>
<tr>
<td>d [mm]</td>
<td>3.98 ± 0.03</td>
<td>6.10 ± 0.04</td>
<td>8.01 ± 0.04</td>
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<td>13.99 ± 0.04</td>
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<tr>
<td>c [m/s]</td>
<td>6378 ± 0</td>
<td>6435 ± 0</td>
<td>6418 ± 0</td>
<td>6397 ± 0</td>
<td>6417 ± 0</td>
</tr>
<tr>
<td>Δc [m/s]</td>
<td>69</td>
<td>45</td>
<td>42</td>
<td>34</td>
<td>24</td>
</tr>
<tr>
<td><strong>Simultaneous measurement without focus correction</strong></td>
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<td></td>
</tr>
<tr>
<td>d [mm]</td>
<td>4.34 ± 0.01</td>
<td>6.36 ± 0.03</td>
<td>8.78 ± 0.04</td>
<td>11.44 ± 0.04</td>
<td>16.84 ± 0.07</td>
</tr>
<tr>
<td>c [m/s]</td>
<td>7005 ± 22</td>
<td>6922 ± 32</td>
<td>7035 ± 31</td>
<td>7332 ± 18</td>
<td>7725 ± 30</td>
</tr>
<tr>
<td><strong>Simultaneous measurement with focus correction</strong></td>
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</tr>
<tr>
<td>d [mm]</td>
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<td>6.04 ± 0.06</td>
<td>7.93 ± 0.04</td>
<td>9.82 ± 0.05</td>
<td>13.36 ± 0.07</td>
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<td>c [m/s]</td>
<td>6360 ± 9</td>
<td>6374 ± 13</td>
<td>6340 ± 21</td>
<td>6286 ± 17</td>
<td>6117 ± 17</td>
</tr>
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</table>

### 4.2 Aluminum

For aluminum (Table 3) the difference between the conventionally measured and the simultaneously (with focus correction) determined sound velocity varies from 0.3 % to 1.7 % for the plates of 4, 6, 8 and 10 mm. The focus correction is also done by the calibration function valid for steel (Figure 11). This means a correction with a function of deviating sound velocity. This calibration function is solely valid for media with a sound velocity of c = 5920 m/s. Applying this curve for focus correction in media with a different sound velocity, it can be expected, that the error increases with an increasing difference of the sound velocities and, additionally, with an increasing focus distance. This is because the influence of the natural focus (and thereby the influence of the sound velocity) on the resulting focus increases with larger focus distances. Since the sound velocity of aluminium is only 8 %
higher than 5920 m/s the error is relatively small. Only for the thicker plate the deviation increases up to 4.5 %. To apply the presented method on arbitrarily materials (with arbitrarily sound velocities), a set of calibration curves for different sound velocities is necessary.

5. Summary and Perspective

It has been shown that the simultaneous determination of sound velocity and thickness of presently two layers is possible. For the first layer the relative error lies in the parts-per-thousand range. Therefore, this approach may render conventional mechanical thickness measurements for the determination of sound velocity in one-layered media superfluous. For the second layer a relative error of less than 1.7 % can be achieved by calculating focus correction curves for the determined sound velocities.

All evaluations are done by the use of synthetic focusing. An additional delayed excitation of the segments during the measurement may improve the results by reducing the signal to noise ratio.

An extension of the proceeding to a third layer should be possible. To ensure low measurement uncertainty for the third layer, sound velocities and thicknesses of preliminary layers have to be well known. For this purpose the accuracy for the second layer has to be improved. In addition, for multi-layered structures an unambiguous allocation of the different echoes to the various interfaces has to be ensured.

Acknowledgment

The authors would like to thank Deutsche Forschungsgemeinschaft (DFG) for their financial support of the ongoing research project KU1075/14-1 and Sonaxis SA for transducer manufacturing.

References