Three-dimensional Sound Field Computation and Optimization of the Delamination Detection based on the Re-Radiation

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Abstract

Air-coupled ultrasound (ACU) is increasingly being used for non-destructive material testing, for instance, to assess cracks, delamination or mechanical properties. The advantage of this method is that no coupling medium has to be used between transducers and probe, which provides high reproducibility and allows for continuous scanning. However, for testing in production, a minimum distance must be often kept between the material and the receiver to avoid sample contamination or transducer damage. As a consequence, the pressure fields diffract around the defects and the ACU images become blurred and show lower defect sensitivity with increasing separation between probe and transducer. Therefore, the minimum detectable delamination size is severely limited. It is of great interest to develop methods that compensate for these phenomena. In this paper a re-radiation method is applied to improve the quality of ACU NDT images. The method combines the Rayleigh-Sommerfeld integral and time-reversal mirrors to determine three-dimensional sound field characteristics with a low measurement effort. The input data is the ACU pressure distribution measured in only one plane arbitrarily separated from the sample. By means of the re-radiation algorithm, it is possible to quantitatively reconstruct the pressure field directly on the probe surface, which compensates for undesired diffraction phenomena and significantly improves lateral resolution and sensitivity. We tested the method on a 22 mm thick medium density fibreboard (MDF) and a distance of 160 mm between the sample an the receiver. This improves the detectable delamination size from 25 mm to under 5 mm and the sensitivity for a 38 mm delamination from -11 dB to -20 dB.

1. Introduction

A standard procedure for the non-destructive quality assurance of board composites is the examination for delamination by means of air-coupled ultrasound (ACU) (1–3). With the help of this method it is possible to assess for example wood-based materials without coupling medium during ongoing production. The excitation is done by an ACU transducer, whereby the distance between transducer and board corresponds to the near-field length. This position is selected because, due to reflections (4), only a small
part of the sound energy propagates through the board. If the board is located at the near field length the transmission signal achieved a maximum and the best signal to noise ratio. The transmission signal is received by means of microphones. Due to the vapors escaping from the freshly pressed boards, different board thicknesses and the high temperatures of the boards (up to 100°C) (5), the receivers must have a minimum distance to the boards. In current industrial use, this distance is in the range of approx. 160 mm. Due to the distance to the board, there is the disadvantage that the resolution decreases considerably compared to the measurement directly over the board and only delaminations with a diameter bigger than approx. 25 mm can be detected.

To simple sound field characterization, for instance, such as calculating the near-field length of a transducer, simple analytical equations exist (6). However the results of this show significant deviations from reality and are not appropriate for inverse algorithms. For this reason, quantitative characterization are carried out in practice by direct measurements of the pressure fields. These are based on a wide variety of measuring principles, such as microphone measurements, Schlieren method and refracto-vibrometry (4, 7–9). The disadvantages of these methods are that it requires a lot of scanning time and experimental effort to make the measurement for the whole characterization of the three-dimensional fields.

There are several approaches to improve the resolution. One method that has been increasingly used in recent years is the de-convolution algorithm (2, 10). This method nicely works for short distances and thin boards, but for real samples and bigger distances between sample and receiver the results get imprecise. Furthermore, the de-convolution method could only calculate amplitude values and not the phase.

In this paper the re-radiation method is used for the characterization of sound fields. This method is based on the Rayleigh Sommerfeld equation and enables the three-dimensional analytical calculation of sound fields. The only input data is the sound pressure distribution of a plane that is oriented parallel to the transducer surface. After describing the theoretical basics, the sound field of an ACU transducer is characterized by using re-radiation. The near-field length is determined and the result compared with the simple analytical equations. Subsequently, the re-radiation method is used to optimize the ACU delamination. A fixed large transducer is used, whose sound field covers the area to be examined. The transmitted sound signal is received by a scanning microphone. The construction is comparable to X-ray radiography. Based on pressure measurements 160 mm above the board, the pressure is calculated directly above the board. This reduced the minimum detection limit for delaminations.

2. Re-radiation method

2.1 Theory

The theory for the three-dimensional sound field reconstruction is based on the equations of (11, 12). A detailed explanation of the whole equations can be found in (6). In the following, only the basic idea of the method is presented. The starting point is the Helmholtz equation for the description of the wave propagation of acoustic pressure waves $p$ in linear, incompressible fluids as a function of the sound speed $c$

$$\nabla^2 p - \frac{\partial^2 p}{\partial t^2} = 0$$  \hspace{1cm} (1)

and an arbitrary pulsed scalar field in 3D-space $p(x, t)$, where $x = (x, y, z)$ and $t$ are
space and time coordinates. By transferring these equations into the frequency domain using the Fourier transformation as well as methods for superposition (Huygen's principle) and other transformations the following relationship results:

\[ p(k,\omega) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p(x,\omega) e^{i(kx+\omega t)} \, dx \, dt \]

\[ \cong \sum_{s=1}^{N_S} (h_S)^2 p(\hat{x}_s,\hat{y}_s,0,\omega) g_{PS}(x-\hat{x}_s,y-\hat{y}_s,z) \]

with

\[ g_{PS}(x) = \frac{e^{ik|x|} \left( \frac{1}{|k|} + i\omega \right) \frac{x}{|k|^2}}{2\pi|k|^2} \]

whereby for the practical implementation, the Rayleigh–Sommerfeld integral is discretized with a finite measurement window \( N_S \) and pixel size \( h_S \). The parameter \( k \) is the wave vector and \( \omega \) the harmonic component.

All further intermediate steps and transformations can be found in detail in the paper of Sanabria et al. (13).

**2.2 Application**

After the measurement of the transient pressure a one plane, the steps described in Figure 2 are carried out to calculate the pressure at any desired location, whereby a distinction between two cases has to be made. The forward re-radiation method (blue colour in Fig. 2) is used to determine the sound pressure at a point, which is further away from the transducer. The backward re-radiation method (red colour in Fig. 2) is used for points closer to the transducer.

In the first step the Fast Fourier Transform (FFT) is used to transform the time waveforms at each measured point \( p(x,y,t) \) to the spectral domain \( p(x,y,f) \). After this, the summations Eq. 3 is used to calculate the forward re-radiation step. Afterwards, the frequency-dependent sound distributions \( p(x,y,f) \) are converted back to the time domain with an inverse FFT (IFFT) \( p(x,y,z,t) \). For the backward re-radiation nearly the same steps and two additional ones are used. Before the FFT and again after the IFFT step the time waveforms are mirrored in time \( p(x,y,z,-t) \).

![Figure 1. Steps of the re-radiation method, the blue steps are for forward re-radiation and the red steps for backward re-radiation.](image-url)
Using the re-radiation method, not only c-scans can be determined, but also time-dependent pressure data. More detailed information of the re-radiation method can be obtained in work of Sanabria et al. (13).

3. Experimental setup

Figure 2 shows the experimental setup to determine the sound pressure at the input plane. The characterization of a sound field is shown for a circular transducer (TX I) with a diameter of 45 mm and an operating frequency of 50 kHz (AT50, AIRMAR Technology Corporation, NH, USA). In order to demonstrate the possibilities of the re-radiation method for optimizing the delamination detection, a larger rectangular (50 mm by 250 mm) transducer (TX II) with an operating frequency of 120 kHz (NCI100-50x250, GMPC, The Ultran Group Inc., State College, PA, USA) is used (see Fig. 2a). The size of the sound field of TX II makes it possible to examine several delamination sizes at the same time, without scanning the receiver. This is similar to X-ray radiography.

![Experimental setup](image)

**Figure 2. Experimental setup.** a) A wood panel is investigated by ACU. b) Delaminations are simulated by round paper shreds with a diameter of 5, 12, 25 and 38 mm

A calibrated pressure-field microphone (RX) (4138, Brüel & 244 Kjær, Nærum, Denmark), with a sensitivity of 10 mV/Pa and a polarization voltage of 200 V is used to measure the sound pressure. This microphone is mounted on a three-dimensional scanner to measure the pressure at defined positions. The positioning reproducibility of the scanning system is ±0.02 mm.

To characterize the sound field the transient sound pressure at a plane separated 85 mm from the transducer is measured. In addition, the sound pressure along the transducer axis over a length of 170 mm is determined to validate the simulation.

For the optimization, a 22 mm thick medium density fibreboard (MDF) is positioned at the near field length of the transducer (200 mm between transducer and board). To
simulate delaminations, paper shreds in the form of circles are positioned on the board. The diameters are 5, 12, 25 and 38 mm (see Fig. 2b) and the transmission signal through the material is measured. The size and resolution of the scanning range depends on the wavelength and the dimensions of the sound field. According to (13, 14), for good results the scanning resolution should correspond to one third of the wavelength and the limits of the scanning area are defined by the -30 dB decrease in relation to the maximum pressure. The calculated resolution for TX I is:

$$\Delta_{TX} = \frac{\lambda}{3} = \frac{346.3 \text{ m/s}}{3 \times 50000 \text{ mm/s}} = 2.31 \text{ mm.}$$

(5)

For the measurements a resolution of 2 mm is used. The area until the amplitude decreases to -30 dB has an experimental determined diameter of 210 mm. As a result a measuring range of 240 mm x 240 mm was selected.

The examinations for the optimization were done with the TX II. The scanning resolution $\Delta_{TXII}$ is calculated to 0.963 mm, whereby the measurement was performed in practice with a resolution of 1 mm. The scanning area for the input plane is 300 mm x 280 mm.

4. Results and Discussion

4.1 Characterisation of the sound field

When designing ultrasonic based measuring systems, it is necessary to have a good understanding of the sound field characteristics. The characteristics of the main and side lobes as well as the position of the near-field length are of particular interest. These properties were determined using the re-radiation method. For this purpose, the sound pressure level of the input plane was measured (shown in red in Figure 3a). The C-scan of the pressure measurement is shown in Figure 3b. Based on this x,y plane, the sound pressure distribution in the x,z plane was determined. The forward re-radiation method was used to calculate the sound pressure distribution in positive z direction (blue area in figure 3a) and the backward re-radiation method to determine the pressure in negative z direction (green area in figure 3a). The result of the re-radiation is shown in Figure 3c. The illustration clearly shows that both the main and side lobes can be reproduced by using the reconstruction method. The main lobe narrows until the near field length is reached and diverges after it. In the near field, strong oscillations can be seen which are due to the narrowband nature of the transducer.

In addition, the near-field length can be determined very precisely. The near-field length, which is equal to the position of the sound maximum, can be determined by the reconstruction for the TX I to 53 mm. This value could be confirmed by means of validation measurements. Figure 3d shows the sound pressure profile along the transducer axis for reconstruction and measurement. From this it becomes clear that the reconstruction shows a really good agreement to the measurement. When comparing the near-field lengths and the pressure distribution in the far-field, hardly any differences can be seen. Only in the area directly in front of the transducer differences are recognized, which are however due to overlays and reflections at the microphone surface. The simple alternative to determining the near-field length $N_F$ is the calculation with the help of an approximate equation, which is based on the diameter of the transducer $D$, the frequency $f$ and the sound speed $c$ in the propagation medium (6):

$$N_F = \frac{D^2 f}{4c} = \frac{(0.045 \text{ m})^2 \times 50000 \text{ 1/s}}{4 \times 346.6 \text{ m/s}} = 73.0 \text{ mm}$$

(6)
A comparison between the simulated and measured value shows a difference of 37.7%. The reasons for the deviation are the vibration of the transducer, which does not correspond to an ideal piston oscillator, but rather to a shielded oscillation and the broadband response of the transducer. Eq. 6 just assumes a single dominating frequency. From this, however, it becomes clear that the approximate formula provides a rough guide value, but cannot be used for the exact design of the system. For this purpose, the re-radiation method offers a good opportunity to make a realistic statement about the sound field with little measurement effort.

![Figure 3. Characterization of the sound field. a) Orientation of the measured plane (red) and calculated planes (blue forward re-radiation, green backward re-radiation). b) C-scans of the pressure distribution of the measured plane. c) Calculated x,z-cross sections. d) Comparison of the pressure distribution on the transducer axis between re-radiation and measurement.](image)

**4.2 Optimization of the detectable delamination size**

In addition to the characterization of sound fields, the re-radiation method also offers the possibility to optimize the detection of delamination with ACU. The test setup for optimization is based on the setup of Figure 2 and is shown schematically in Figure 4a. The input data for the re-radiation method is plane A, which is located 160 mm above the board and presents the position, where the pressure is measured in the industrial application in an ongoing production. The sound pressure distribution is shown as a C-scan in Figure 4b. From this Figure it becomes clear that the delamination with a diameter of 25 or 38 mm leads to a recognizable decrease in amplitude, but the delamination contour cannot be identified. For delaminations with a diameter of 12 mm,
just small amplitude variations can be detected and the delaminations with a diameter of 5 mm are not recognizable. These findings are confirmed by the profile on the y-axis (Fig. 4c).

Figure 4. Pressure field 160 mm above the board. a) Experimental setup and plane position. b) C-Scan. c) Pressure profile.

The maximum drop is only -11.8 dB for the largest flaws and no change in amplitude can be detected for the smallest flaws. Based on the measurement of plane A, the sound pressure distribution is calculated in plane B (5 mm above the board). To validate the simulation, this plane is also measured with the microphone. The pressure profile on the y-axis (Fig. 5) shows a very good agreement; even inhomogeneities in the material as well as scattering signals are mapped by means of the simulation.

Figure 5. Pressure profile comparison between measurement and re-radiation for a plane 5 mm above the board (plane B).

In contrast to the measurement at a distance of 160 mm, all simulated delaminations are detected in the C-scan and the amplitude drop is much larger than in the profile at plane A. Even the small delaminations achieve a drop of almost 10 dB and the decrease for the larger flaws even exceeding 20 dB. The contours of the delaminations can be seen even more clearly. This can be recognized by the steeper slope in the profile at the delamination edges.

The result of these investigations is that the measurements taken 160 mm above the board reveal only large defects. Using the re-radiation method, it is possible to
determine a realistic sound pressure distribution near the board and to detect delaminations in the range of 5 mm.

5. Conclusions

The re-radiation method offers the possibility to calculate and characterize the sound field of a transducer with the sound pressure of only one measured plane. Not only static amplitude values but also transient signals can be determined. Using this method, the characteristic values important for NDT, such as the near-field length and the characteristics of the main and secondary lobe, can be calculated with high precision. In addition, re-radiation can be used to optimize delamination detection. Based on the sound pressure distribution measured 160 mm above the material, the sound pressure directly above the board can be precisely calculated. This step makes it possible to detect flaws in a single-digit millimeter range with a 120 kHz transducers.

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References

