DETECTION OF FLAWS WITH LAMB WAVES AND AIR-COUPLED ULTRASOUND

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Abstract
Lamb waves are a form of guided waves propagating along plates to larger distances, which is advantageous for testing inaccessible structures. They appear in several modes, whose phase and group velocity depends on the frequency. In case of air-coupled probes usually frequencies below 1 MHz are used. Then we are dealing with only a few modes, substantially simplifying the signal interpretation. Another advantage of air-coupled ultrasonic testing is avoiding direct contact with the inspected object.

In this work Lamb waves were excited and received in a homogeneous isotropic material with air-coupled transducers in the kHz range. We investigated the transducer beam profile in detail. We present the application of Lamb waves to the detection of different sized notches implemented in a 3-mm-thick aluminium plate.

Keywords: Lamb waves, air-coupled probes, beam profile, ultrasonic testing

1. Introduction
Sensitive surfaces and complicated geometries frequently limit the applicability of ultrasonic inspection. In such cases air-coupled ultrasound can tackle the problem of coupling. For objects with limited accessibility and adequate geometry Lamb waves may be used. In this paper the combination of air-coupled probes and Lamb waves has been investigated, with the aim of improving inspection of difficult test objects such as objects with corrosive surfaces and limited accessibility.

Lamb waves are ultrasonic waves propagating in a medium between two parallel surfaces [1, 2]. Since 1990s they are increasingly used in non-destructive testing (NDT) because of a boost of computing power, which is necessary for digital signal processing. Their wavelength is about the same size or larger than the plate thickness. Since they propagate in two dimensions, their divergence is smaller than the divergence of longitudinal and shear waves propagating in a three-dimensional test object. Therefore, they can propagate to larger distances. Because of the geometrical conditions in a plate, Lamb waves behave differently than longitudinal and shear waves: they form several symmetrical and antisymmetrical modes which propagate dispersively.

The mode conversion at the flaws and the dispersive nature of Lamb waves can make the signal interpretation difficult. That is why the main challenge in the use of Lamb waves in NDT is the excitation of a single mode.

Many studies dealing with detection of flaws are focused at the interaction of Lamb waves with notches of infinite length. The reflection coefficient for a reflection on a defect depends on the used mode, on the product of the frequency and the plate
thickness and on the geometry of the flaw [3]. Ref. [4] describes this complex dependency for \( A_0 \) mode reflected from notches of infinite length.

There exist several methods for a selective excitation of modes. Well known is the use of periodic arrays. Another possibility is to apply an angle beam probe with a suitable angle, or to use phased array transducers [5]. Phased arrays have the advantage that the angle can be electronically controlled. The angle between the wave front and the plate is adjusted so that the components of the wave vector in the wedge and the wave vector of the aimed mode in the plate are the same at the plate surface. The same principle is applied for the excitation of Lamb waves with air-coupled transducers (Figure 1) [6]. The choice of a single mode is achieved through the choice of the angle of incidence \( \alpha \). In recent years some air-coupled phased array systems have been developed to enable electronic control of the angle [7].

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\sin \alpha = \frac{\lambda_{\text{air}}}{\lambda} = \frac{c_{\text{air}}}{c_{\text{phase}}}
\]

Figure 1. Excitation of Lamb waves with an air-coupled ultrasonic probe.

The excitation of Lamb waves with air-coupled ultrasonic probes has two advantages: (i) there is no contact with the test object and no necessity for a coupling medium, and (ii) at low frequencies typical for air-coupled probes there are fewer modes. The large difference between acoustic impedances of air and other media causes very low transmission at the interface between the transducer and the air and between the air and the tested object. This is why high amplifications are required. To improve the signal-to-noise ratio low-noise amplifiers are used. At such high amplifications the entry echo is longer, overlapping with the measured signal, which makes pulse-echo testing more difficult. This problem may be solved with new transducer materials like cellular polypropylene ferroelectret films, which reduce the impedance mismatch between the air and the transducer [8].

In this work we studied the application of air-coupled ultrasound to excitation and detection of Lamb waves, in particular the influence of the notch length on the detection of notches for a plate with a two-side and one-side accessibility.

2. Measurements of the beam profile

When planning the experiment, the beam profile should be taken into account. Possible side lobes could excite some unwanted modes. Therefore, the beam profile of
two air-coupled probes was investigated. The same probes were used in the experiments with the plates.

A ball with a diameter of 8 mm was moved in the field of a probe with the help of a scanner. The reflected signal was recorded with the same probe. To take into account the long entry echo, a reference measurement without the ball was taken and subtracted from the measured signal.

These measurements were performed on two Ultran GN-55 probes, the same probes that were used later in the experiments with the plates. They both have a middle frequency of approx. 330 kHz, a band width between 50 and 100 kHz and a near field length of approx. 55 mm. The results for one of these probes (Figure 2 and Figure 3) are presented in C-scans, showing side lobes at an angle of 8° in relation to the main lobe direction. A scan in a plane along the sound beam axis (Figure 2) reveals only the strongest side lobe, while the others can be recognized in scans perpendicular to the sound beam axis (Figure 3).

All measurements from this paper were performed with an ultrasonic measurement system UTPC 4000 AirTech specially developed for air-coupled transducers [9].

![Figure 2. Beam profile of a probe Ultran GN-55 in a plane along the sound beam axis (C-scan). z is the distance to the probe. The colour represents the amplitude in dB.](image)

![Figure 3. Beam profile of a probe Ultran GN-55 in a plane perpendicular to the sound beam axis (a) in near field (z = 30 mm), (b) near the focus (z = 50 mm) and (c) in far field (z = 90 mm). The colour represents the amplitude of the C-scan.](image)
3. Detection of defects in a plate

3.1 Method

We have investigated the reflection of $A_0$ mode from notches of different lengths. Three notches were inserted into a 3 mm thick aluminium plate.

The choice of the notch width was governed by the need to simulate cracks. The reflection coefficient depends strongly on the notch width: the amplitude of the reflected signal is a cosine-shaped function of the width [4]. For a width approaching zero – hence for a crack with an opening in the μm-scale – the amplitude achieves its first maximum, it drops with the growing width and grows again to achieve its second maximum. This second maximum is achieved at the width of $\lambda/2$, where $\lambda$ is the wavelength of the Lamb wave in the remaining plate thickness. Because of technical difficulties to produce a very narrow notch, the width corresponding to the second maximum was used in this experiment. To find this width experimentally, measurements were performed on notches with a varying width. The second maximum appeared at the width of 2.7 mm, so that this width was chosen for the experiment with the varied length.

The transducers were positioned at the same side of the plate as illustrated in Figure 4. B-scans were taken in the direction parallel to the notch and the reflected signals were recorded. Probes Ultraman GN-55 described in Section 2 were used. To achieve the best coupling the distance to the plate was 55 mm, which is the near field length. The angle of incidence $\alpha$ was optimised for the $A_0$ mode and was approx. 9°. At this angle side lobes do not cause any difficulties. The distance between the transducers was 70 mm. The distance $\Delta x$ between the beam entry into the plate and the notch varied between 100 mm and 160 mm. The three notches had a depth of 1 mm and the following lengths: $L = 6$, 20 and 60 mm.

![Figure 4. Experimental setup for measurements on a plate with notches.](image-url)
The angle $\alpha$, but also the squint angle (defining the orientation in the x-y-plane) were adjusted to get an orientation of the probes optimised for a maximum signal. The overlap of the sound fields of both probes in the plate defines the sensitivity area in the x-direction. Acoustic shielding between the probes (not illustrated) was necessary to avoid adulterant influences by the direct reflection from the plate. Noise was reduced through averaging 16 measurements.

### 3.2 Results

Some of the measurement results are presented in Figure 5. A Gaussian lowpass filter has been applied to reduce the noise. The signals from the 60 mm and 20 mm long notches are clearly noticeable, while the 6 mm notch is close to the noise level. With an increasing distance to the notch – in our case 160 mm instead of 100 mm – the signal-to-noise ratio gets smaller. With a number of averaged measurements higher than 16 smaller signals can be detected and testing at larger distances can be achieved. This has been proven experimentally. However, improvements of the signal-to-noise ratio have to be paid with a longer inspection time. For example, the measurements with 16 scans presented in Figure 3 took between one and three minutes.

![Figure 5. B-scans of the signal reflected from the notches, 16 measurements averaged. $\Delta x$ is the distance to the notches and $L$ is the notch length.](image_url)
5. Conclusions

Notches of different lengths inserted into a 3 mm thick plate were detected with Lamb waves excited with air-coupled ultrasound. The $A_0$ mode was selected by adjusting the incidence angle $\alpha$. The notch width was chosen so that the reflected signal has the same amplitude as that of a crack with the same length and depth. With the experimental setup described in this paper cracks 20 mm in length were clearly detected. The detectability depends on the number of averaged measurements and on the distance to the notch. More averaged measurements and hence longer testing enables inspection at larger distances.

Previously the beam profile had been measured. These measurements made it clear, that the side lobes should be considered during the planning of experiments, because they could excite or receive some unwanted modes.

The length of the interface echo has a high influence on the quality of the measurement result. Development of wideband transducers with a shorter interface echo would enable testing with the pulse-echo technique, which would simplify the experimental setup.

Excitation with air-coupled probes is a promising technique for components with sensitive surfaces or complicated geometries, because it requires no coupling. Combined with Lamb waves it is especially well suited for thin parts with limited accessibility. Future work will deal with further improvements of the signal-to-noise ratio by using alternative transducer materials like ferroelectrets, optimised excitation pulse form and low noise matched amplifiers.

References