# TIME-RESOLVED LINE FOCUS ACOUSTIC MICROSCOPY USING LAMB WAVES FOR MATERIAL CHARACTERIZATION OF THIN PLATES

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## INTRODUCTION

A line focus acoustic transducer is used to excite and detect Lamb waves in a thin plate in order to determine elastic constants. The response of the transducer-couplant-plate system to a pulse with a center frequency of 8 MHz has been simulated, and a preliminary series of corresponding measurements has been carried out.

Elastic constants have been determined by a systematic comparison of the time delays of wave-mode-responses obtained from the theoretical model and the experiment.

In time-resolved acoustic microscopy the specimen is shifted into the defocussed region of the lens and remains at one single position during the measurement. This technique represents an alternative to the V(z) approach in which a high frequency toneburst is used, and the voltage at the transducer of the lens is measured while the specimen is moved within the defocussed range of the lens. In contrast to the V(z) technique, in which the integral over the entire response, consisting of several travelling modes and reflections, is recorded, it is possible using the time-resolved technique to analyze the components of the response in the time domain. This is of particular interest since different material constants dominate the propagation velocity of different Lamb-wave modes.

Time-resolved line-focus acoustic microscopy has proven to be a useful technique to measure the elastic near surface properties of anisotropic, homogeneous materials, see [1] and [2]. The time resolution of the signal can be done with a lower frequency compared with the V(z) measurement methods in which frequencies of 200 MHz or higher are used. This low frequency transducer has a radius of 25.4 mm.

## EXPERIMENTAL SETUP

The experimental results presented in this paper were obtained with the time resolved ultrasonic measurement system shown in Figure 1. The key part of the whole set-up is the line-focus transducer which consists of a PVDF (polyvinyliden fluoride) film glued on an epoxy backing. This highly effective low cost device has been invented by Xiang, Hsu,

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and Blessing [3] and an improved version, having a wider aperture angle, has been manufactured at the Center for Quality Engineering and Failure Prevention, Northwestern University. The particular advantage of a line-focused sound field is the ability to determine material properties of anisotropic material. The results presented in this paper are, however, for an isotropic specimen.

The line-focus transducer was attached to a Panametrics™ Hyscan system and the specimen was submerged in a water tank which can be rotated. A Panametrics™ pulser-receiver (5055 PR) was used to excite the acoustic waves and to detect the voltage response at the transducer. The center frequency of the pulse is about 8 MHz. The transducer output signals were digitized by a Tektronix™ TDS-540 four channel digitizing oscilloscope and stored by a personal computer.

During the measurement process, the specimen is submerged in water and located in the defocussed region of the transducer and the wave fronts strike the specimen at all angles within the aperture angle $\alpha$, as illustrated in Figure 2. Distilled water is used as a coupling fluid in order to provide electric isolation.

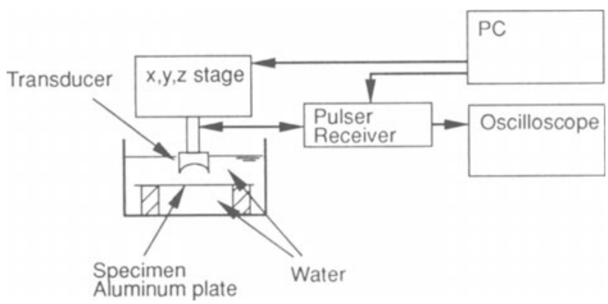


Figure 1. Experimental setup.

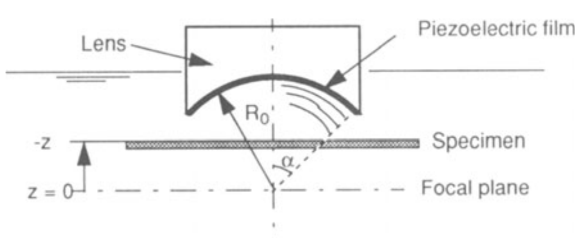


Figure 2. Transducer and specimen.

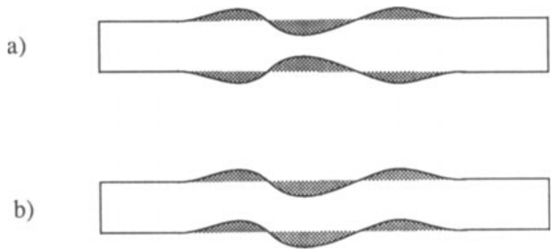


Figure 3. Illustration of the first symmetric Lamb wave mode a) and the first antisymmetric Lamb wave mode b).

For an aluminum plate with a thickness of 76 μm the first symmetric and the first anisymmetric Lamb wave modes, illustrated in Figure 3, can be excited. In general Lamb waves are dispersive which means that their propagating velocities are frequency dependent. For the configuration (frequency, plate thickness, plate material) described above, however, the dispersive effects are small and the distortion of the travelling pulses is minor. Due to the different propagation velocities, the first symmetric and the first antisymmetric Lamb wave modes radiate at different angles into the coupling fluid leading to different arrival times at the piezoelectric film. Thus the modes can be separated in the time domain.

## THEORETICAL MODEL

In order to determine the geometrical and material parameters which are governing the response to a pulse, a theoretical model predicting this response has been derived and the values of the parameters have been obtained in an iterative way.

The simulation model is based on Fourier analysis and can be outlined as follows:

The output voltage v(t) which can be measured at the piezoelectric film, can be written in terms of a convolution product of the input pulse p(t) and the transfer function h(t,z). The transfer function h(t,z) contains all information about the transducer geometry, the coupling fluid, and the dynamic behavior of the plate.

$$v(t,z) = p(t) \otimes h(t,z) \tag{1}$$

$$V(\omega,z) = P(\omega)\ H(\omega, z) \tag{2}$$

| | |
|---|---|
| $v(t,z)$ = | Output voltage at the piezoelectric film. |
| $p(t)$ = | Input pulse. |
| $h(t,z)$ = | Fourier transform of the transfer function H of the lens-fluid-plate system |
| $V(\omega,z)$ = | Output voltage in frequency domain. |
| $P(\omega)$ = | Input pulse in frequency domain. |
| $H(\omega,z)$ = | Transfer function in frequency domain. |

## TRANSFER FUNCTION

The transfer function consists of an emitting lens function $L_1$ and a receiving lens function $L_2$. This terminology has its origin for lenses (transducers) in which the acoustic waves are not generated at the concave side of the lens. In the case outlined in this paper, however, the piezoelectric film transducer is directly glued on the concave backing and therefore $L_1 = 1$.

$$H(\omega,z) = \int_{-k_M}^{k_M} L_1 L_2(k_x)\, R(k_x)\, e^{2i(k_w R_0 + k_z z)} dk_x \quad (3)$$

$$L_1 = 1 \quad (4)$$

$k_m$ denotes the limiting wavenumber which can be received by the lens.

The receiving lens function $L_2$ represents the integral over the entire aperture angle in order to collect the reflected responses from all directions.

$$L_2 = \int_{-\alpha}^{\alpha} \cos\left(\varphi - \mathrm{asin}\left(\frac{k_x}{k_w}\right)\right) d\varphi \quad (5)$$

$R(k_x)$ describes the reflection function of a submerged thin plate. In this investigation the reflection function was determined following Chimenti and Nayfeh [4].

$$R(k_x) = \text{Reflection function of a thin plate} \quad (6)$$

## HOW TO FIND P(ω)

Since the input pulse of the system in the time domain,p(t), is not known a priori, it has to be determined first. Therefore the response of a system having well known material parameters, has to be measured. A thick aluminum block, representing an isotropic elastic half-space, has been chosen for that purpose. For this configuration the voltage response versus time v(t,z=0) has been recorded while the surface of the aluminum block was located in the focal plane of the transducer, which minimizes the influence of the material properties on the response.

In a second step, the v(t,z=0) was transformed to the frequency domain using the FFT leading to V(ω,z=0).

Finally the transfer function $H_{AB}(\omega,z=0)$ for the aluminum block is calculated and the input pulse in the frequency and time domains is obtained according to Equation (7) and Equation (8).

$$P(\omega) = \frac{V(\omega, z=0)}{H_{AB}(\omega, z=0)} \quad (7)$$

$$p(t) = F^{-1}\{P(\omega)\} \quad (8)$$

in which $F^{-1}$ denotes the inverse Fourier transform.

The input pulse determined in that way was then used to simulate the response of the thin aluminum plate.

## SIMULATIONS vs. MEASUREMENTS

The following series of diagrams shows simulated (solid lines), and measured (dashed lines) responses of a submerged aluminum plate with a thickness of 76 µm to a pulse. The distance z between the transducer and the specimen is the only parameter being varied in this series. The aperture angle of the lens was $45^{o}$.

Figure 4 shows the case when the waves are focused on the surface of the plate. Even though Lamb waves are excited in this case, only the direct normal reflection can be measured with the transducer. The influence of the plate material to the direct reflection is small and the shape of the response is congruent to the one of the emitted pulse. The peak amplitude of the diagrams in which z=0, was used to normalize the measured as well as the simulated signals of the following series. The absolute time scale has no meaning and only the time delays between the responses from different modes should be considered.

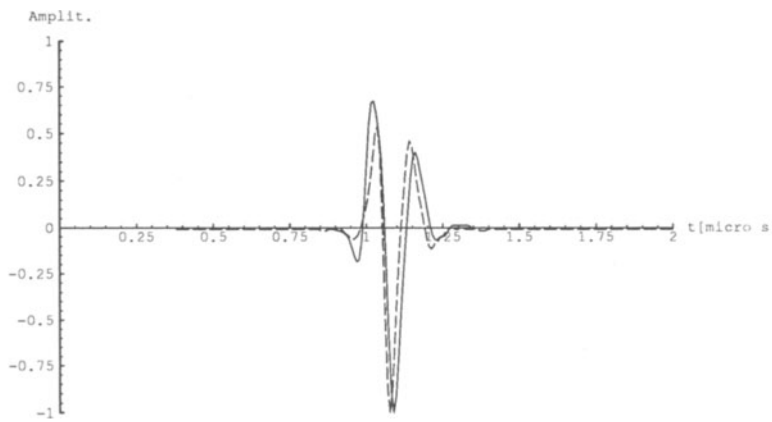


Figure 4. Simulated (solid lines) and measured (dashed lines) responses for z = 0.

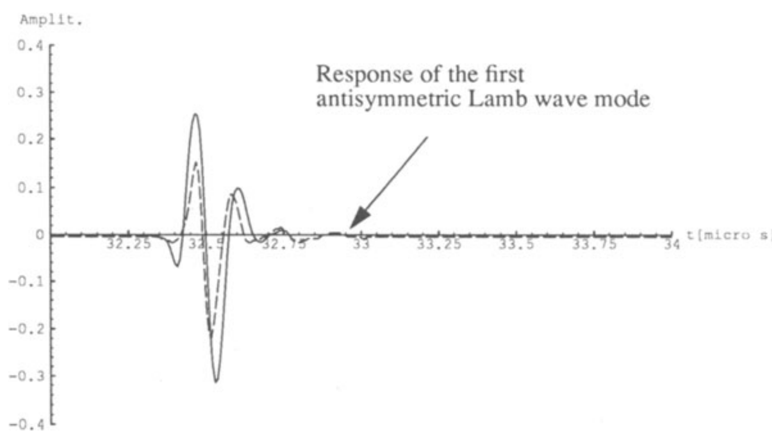


Figure 5. Simulated (solid lines) and measured (dashed lines) responses for z = -1 mm.

In Figure 5, the response of the highly damped first antisymmetric mode is slightly visible (see arrow).

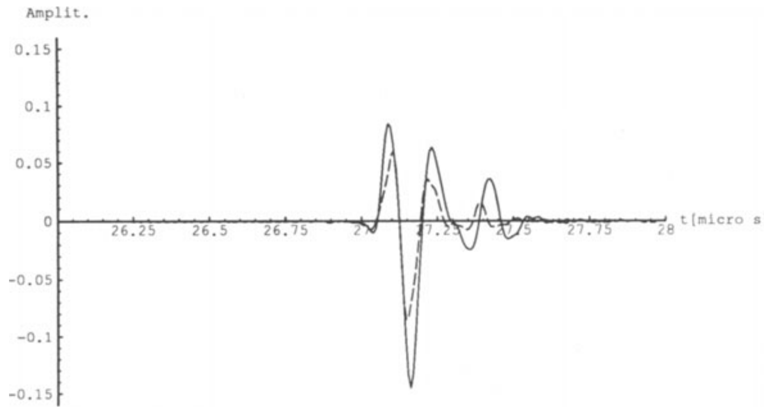


Figure 6. Simulated (solid lines) and measured (dashed lines) responses for z = -5 mm.

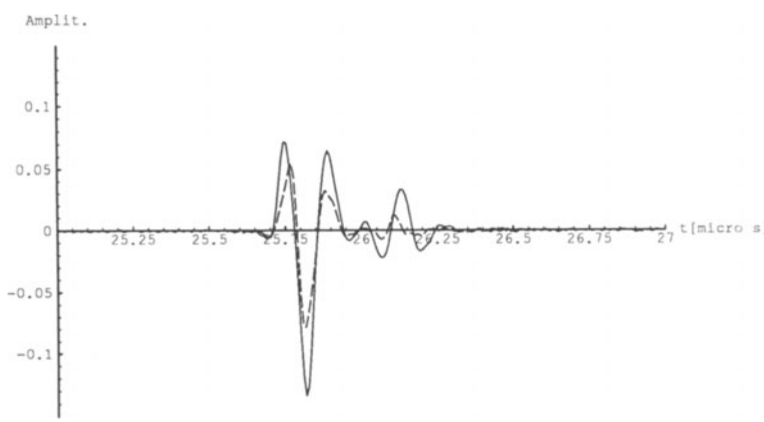


Figure 7. Simulated (solid lines) and measured (dashed lines) responses for z = -6 mm.

The more the specimen is shifted into the defocussed range of the transducer, the more the response of the first symmetric mode becomes visible (see Figure 6,7, and 8) whereas the direct, normal reflection remains always present. The response of the first symmetric mode is clearly visible in Figure 8.

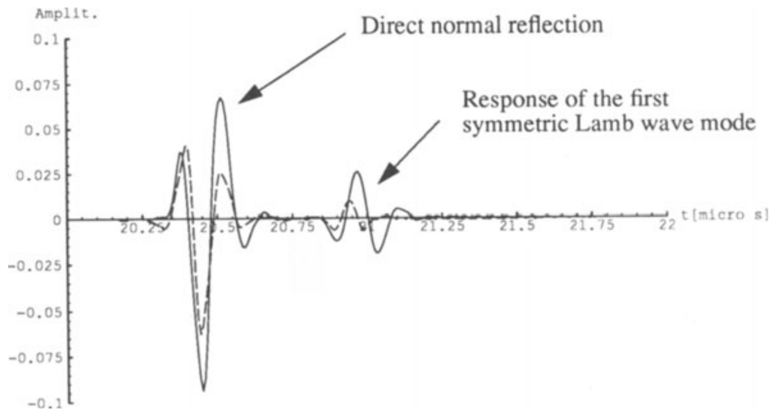


Figure 8. Simulated (solid lines) and measured (dashed lines) responses for z = -10 mm.

## RESULTS AND CONCLUSION

To determine the material constants, the arrival time of the response from the first symmetric Lamb wave mode has been used. Figures 5 to Figure 8 show that the shapes of the simulated curves do not match the measured curves perfectly. The most probable reason for this discrepancy is the fact that the propagating waves in the plate are exponentially decaying, an effect which is not considered in the present simulation.

In order to achieve the best fit of the arrival time, the following material parameters for the aluminum plate have been found:

$\lambda = 5.48*10^{10}$ N/m$^2$
$\mu = 2.65*10^{10}$ N/m$^2$

Thus, a first series of evaluations shows that time resolved line focus acoustic microscopy can be used to measure elastic constants of thin films.

Future work should deal with improvement of the simulation, extension to anisotropic thin films, as well as with quantitative determination of static stress in thin films.

## ACKNOWLEDGEMENT

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