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# Non-contact ultrasound with optimum electronic steering angle to excite Lamb waves in thin metal sheets for mechanical stress measurements

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***Abstract*—A non-contact method for measuring mechanical stress in thin steel sheets using air-coupled ultrasound with electronic beam steering is presented. This allows the automatic adjustment of the optimum steering angle to excite the target Lamb wave mode for a wide range of thicknesses of the specimens, which is advantageous compared to conventional setups with fixed angles. By inducing mechanical stress into the metal sheet, a change of group velocity is measurable, as expected.**

**The experimental setup consists of our 2D ultrasonic phased-array, positioned above a steel sheet, emitting an ultrasound beam at an arbitrary angle. At the opposing end of the steel sheet, a microphone receives the leaky Lamb wave. We electronically sweep the angle of the ultrasound beam, matching the optimal coupling angle for different thicknesses of the steel sheets. Further, we demonstrate a sample NDT application, where we induce mechanical stress into the steel sheet, changing the group velocity in the material. Based on the arrival times measured with an oscilloscope, we calculate the group velocities for variable mechanical stresses.**

**The signals received by the microphone show that the acoustic signal caused by the Lamb wave arrives before the air-coupled component of the ultrasound. The group velocities measured show good agreement to a linear relation for mechanical stresses up to 100 MPa. Moreover, the measured group velocities match the expected values based on the calculation of the proper dispersion curves for asymmetric and symmetric Lamb waves for phase and group velocity at 40 kHz and the given thickness of the steel sheet.**

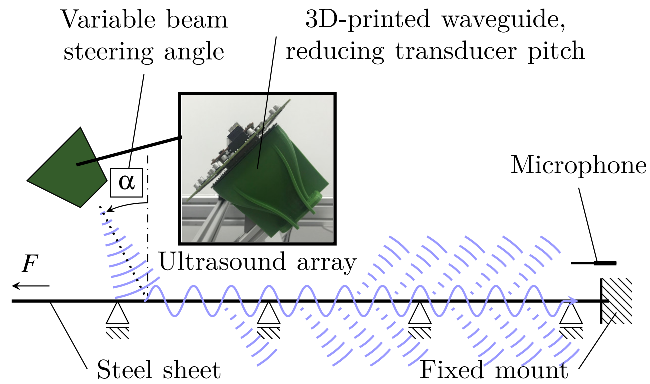


Fig. 1. Schematic of the non-contact ultrasound experiment. Our air-coupled ultrasonic phased-array emits an ultrasonic beam at a certain angle $\alpha$, matching the necessary coupling angle for exciting a Lamb wave in the steel specimen. The Lamb wave travels along the specimen, while permanently leaking ultrasound in the surrounding air. A microphone receives the emitted ultrasound. Additionally, the specimen may be exposed to mechanical stress via a force $F$ (screw in the mounting mechanism).

## I. Introduction

Traditional ultrasound systems for non-destructive testing (NDT) require the use of a coupling agent such as water or gel for efficient coupling between the transducer and the specimen to inspect. The reason is the impedance mismatch of the usual rigid transducer material to air and again to the specimen. Several concepts work around this impedance mismatch, allowing non-contact ultrasound (NCU) inspection of specimens without liquid or solid contact. This is desirable, because a coupling agent that might contaminate either the part itself or the environment is not required. Two concepts generate the ultrasound within the part itself, circumventing the impedance mismatch completely: Electro-magnetic acoustic transducers (EMAT) excite waves in specimen using magnetic fields. This requires the specimen to be made of electrically conducting materials, limiting the method to metals and therefore excluding e.g. fibre-reinforced composites and ceramic materials. The second concept uses short laser pulses that heats up a spot on the specimen's surface instantaneously, leading to a rapid thermal expansion, and, thus, the excitation of a mechanical wave [1]. The laser excitation is limited by the amount of energy induced into the specimen preventing ablation that damages the specimen. For the special case of Lamb waves [2], excitable in thin plates compared to the wavelength in the material, the coupling from a sound wave propagating in a surrounding medium such as air is feasible [3]–[5]. The coupling mechanism is reciprocal, i.e. when it is possible to couple a Lamb wave into the material, the Lamb wave radiates or *leaks* ultrasound into the surrounding medium as well. This even allows using ultrasound leaked from one sheet to inject a Lamb wave into a second sheet placed in parallel [6]. The coupling from a bulk wave into the plate is only possible when the wave front arrives at a certain coupling angle $\alpha$. This angle $\alpha$ is dependent on the thickness and the combination of material of the sheet and the surrounding medium. The wave front leaking out into the surrounding medium has this same angle.

In commonly used test setups, a wedge is constructed fixing the transducer to a certain $\alpha$ with respect to the plate for each thickness and material combination. The wedge might be mechanically adjustable, but always requires adaptation to the particular combination of frequency, material type and thickness.

The objective of this work is to show that the same air-coupled ultrasound source can be used to excite Lamb waves in steel sheets of different thicknesses without changing the mechanical orientation, always using the particular optimal coupling angle, just by electronic beam steering.

## II. Theory of Operation

The conversion of a sound wave in air to a Lamb wave in the plate requires two conditions to be fulfilled: First, the coupling angle $\alpha$ needs to satisfy

$$\alpha = \arcsin\left(\frac{c_{\mathrm{Air}}}{c_p}\right), \tag{1}$$

with $c_{\mathrm{Air}} = 343\,\mathrm{m/s}$ and $c_p$ is the phase velocity of one of the excitable modes at the certain combination of thickness and frequency in the sheet (Fig. 2). Second, from the definition of the arcsin-function, $c_p$ has to be faster than the speed of sound in air, i.e.

$$c_p > c_{\mathrm{Air}}. \tag{2}$$

Here, $\alpha$ is the angle between wave front in propagation direction in air to the perpendicular line to the sheet (Fig. 1).

For each product of frequency and thickness, there might be zero, one or even multiple solutions for $\alpha$, depending on the excitable modes at this operation point (Fig. 2). In our experiment, we only consider one material, steel, type S235JR. Furthermore, we select the thickness of the sheet to ensure that there are always only two solutions for $c_p$: The symmetric $S_0$ and the asymmetric $A_0$-mode (Fig. 2). However, we are only investigating the $A_0$-mode and use it solely for calculating both the phase and group velocities $c_p$ and $c_g$. Since the ultrasonic transducers are excited with a sine or square-wave pulse with a finite number of periods, the actual transmitted pulse spectrum contains multiple harmonic frequencies. Therefore, the group velocity $c_g$ must be considered whenever the speed of the actual pulse within the sheet is determined. In our case, $c_g$ is always larger than $c_p$ by an approximate factor of 2 (Table I).

Both $c_p$ and $c_g$ are depending on the thickness of the steel sheet (Fig. 2). This is the reason why $\alpha$ is different for each thickness (Eq. 1). We overcome this issue by employing electronic beam steering as shown in a number of other experiments [7]–[9]. The operating frequency of 40 kHz of the used ultrasonic phased-array results in a high sensitivity of the $A_0$-mode in both phase and group velocities $c_p$ and $c_g$ regarding both the thickness and frequency (Fig. 2). This allows the measurement of the sheet thickness using the group velocity $c_g$, as long as all other parameters of the setup are known. Besides the demonstration of exciting Lamb waves inside the steel sheet, we demonstrate a simple NDT application, where we pull the sheet, which uniformly changes the group velocity $c_g$ as it is depends on the stress condition in the sheet.

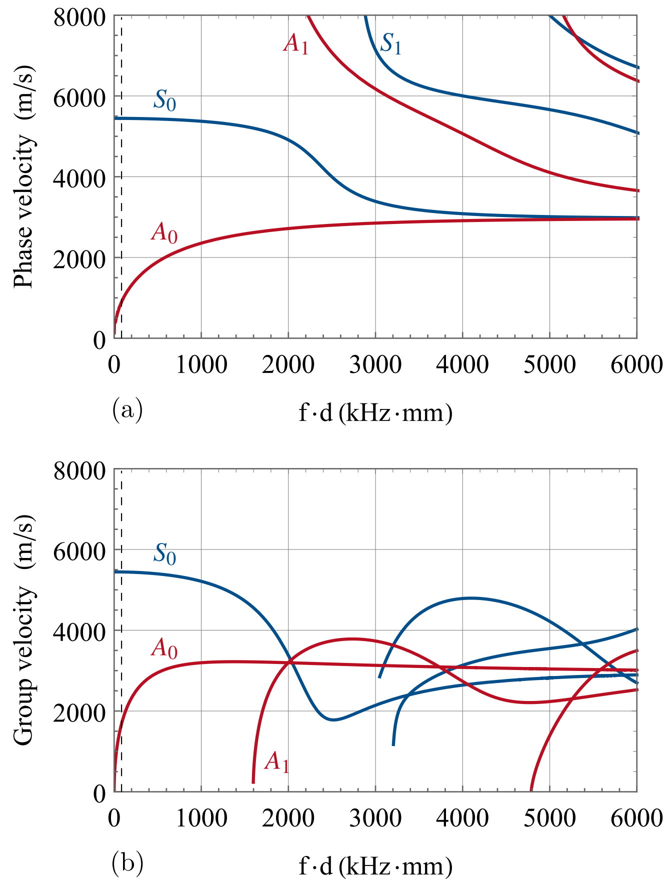


Fig. 2. Dispersion diagram for steel, type S235JR, phase velocity (a) and group velocity (b). In our experiment, the $A_0$ and $S_0$ modes are of main interest excited by our array transducer, operating at 40 kHz. This corresponds to a thickness $d$ of up to 1 mm (dashed line). The calculations are done using Mathematica (Version 11.3, Wolfram Research Inc., Champaign, IL, USA).

## III. Experimental Setup

We use sheets made of steel, type S235JR, as specimen, with a size of $2\,\mathrm{m} \times 0.1\,\mathrm{m}$ and thicknesses of 0.5 mm, 0.8 mm and 1.0 mm. One of the sheets is mounted in a frame made from aluminum extrusions, equipped with a mechanism to pull the sheet (Fig. 3). The sheet is supported by a number of spikes, ensuring that it is not bent due to its own weight. A pulling mechanism applies a force of up to 2500 N. The force applied is measured by a force gauge attached between the pulling mechanism and the specimen.

Our custom ultrasound array, has a uniform rectangular, $8 \times 8$, $\lambda/2$-aperture, and transmission frequency of 40 kHz [10]. As the array is made of commercially available ultrasound transducers (MA40S4S Murata Seisakusho, Kyōto, Japan), exceeding a diameter of $\lambda/2$, a 3D-printed waveguide is used to reduce the inter-element spacing to $\lambda/2$, ensuring grating-lobe

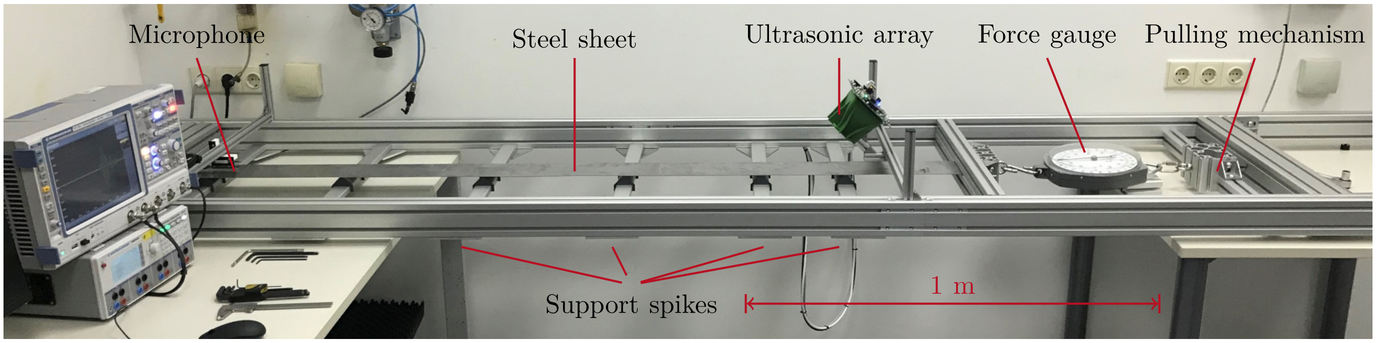


Fig. 3. Setup consisting of a frame made of aluminum extrusions, holding all the components of the experiment: Phased-array for excitation, the steel sheet as specimen, supported on spikes, a microphone as receiver and a mechanism required for applying a force $F$ to the specimen (pulling mechanism). The array is pre-inclined to an angle of 45° as steering is more precise for steering angles around 0° compared to the necessary coupling angles of 50.8°, 38.1° and 33.6° for the three used specimen of 0.5 mm, 0.8 mm and 1.0 mm, respectively.

free beamforming [10]–[13]. The custom-built electronics allow beam steering with a step size of 1° over an angular range of ±55° in two dimensions. Only the elevation dimension, which affects the coupling angle $\alpha$, is used in this experiment.

The leaky Lamb wave is captured using a MEMS microphone (SPU0410LR5H-QB, Knowles Electronics, LLC. Itasca, IL, USA) connected to an oscilloscope (RTE1024, RHODE & SCHWARZ GmbH & Co. KG., Munich, Germany). No additional amplifier is required. The microphone is mounted on a custom made PCB containing the power supply and connectors to the oscilloscope.

As the group velocity in the steel sheets only is higher by a factor of 2.5 for the worst case of a thickness of 0.5 mm, ($c_p = 862{,}85$ vs. $c_{\text{Air}} = 343\,\text{m/s}$), the sound path in the steel sheet must be long enough to ensure that the Lamb wave arrives before the acoustic wave in air. This allows a clear distinction of the two different signals (Fig. 4). The chosen length of the acoustic path within the sheet is approximately 1.3 m and is slightly different for each thickness as the position of arrival from the air-path on the sheet is dependent on the coupling angle $\alpha$. For each steel sheet, the ultrasound array is programmed to sweep the steering angle from 0° to 90°. At each angular step, a pulse of eight cycles is emitted. The received maximum amplitude of the Lamb wave pulse is plotted as a function of $\alpha$ (Fig. 5).

Next, a force is applied to the steel sheets and the time of arrival of the leaky Lamb wave is recorded. A tensile stress in the steel sheet causes a change in both, the group and phase velocity in the steel sheet. However, the change is too small to cause a significant difference in the coupling angle. Therefore, the relative change of the group velocity for all steel sheets is recorded as a function of mechanical stress (Fig. 6).

## IV. Results and Discussion

All three curves of received amplitude over $\alpha$ show a similar shape consisting of one distinct global maximum and several local maxima (Fig. 5). This matches the shape of the directivity pattern of an 8 element, $\lambda/2$-line array, consisting of one distinct main lobe surrounded by several weaker side lobes and is

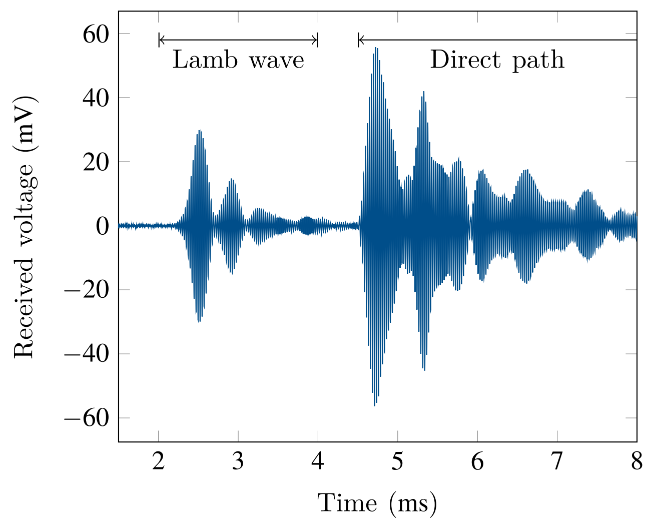


Fig. 4. Acoustic signal received by the microphone, caused by a pulse of eight periods using an acoustic path length of 1337 mm in the steel sheet. Two distinct pulses are clearly visible: The first pulse is the signal originating from the leaky Lamb wave, outrunning the direct sound path due to the higher group velocity in the steel specimen. The second pulse is the signal from the line of sight, in addition to reflections, arriving later in time, although the geometric path length is shorter.

therefore an expected behavior. This proves that the phased-array not only injects Lamb waves at the main lobe angle, but also at the side lobe angles at lower amplitudes. The position of each main maximum matches the expected optimum coupling angle (Table I).

TABLE I
CALCULATED PHASE AND GROUP VELOCITIES $c_{p,\text{calc}}$ AND $c_{g,\text{calc}}$, MEASURED GROUP VELOCITY $c_{g,\text{meas}}$ AND CALCULATED AND MEASURED ANGLES $\alpha_{\text{calc}}$ AND $\alpha_{\text{meas}}$ FOR ALL THREE STEEL SHEETS FOR AL THREE THICKNESSES $d$.

| $d$ | $c_{p,\text{calc}}$ | $c_{g,\text{calc}}$ | $c_{g,\text{meas}}$ | $\alpha_{\text{calc}}$ | $\alpha_{\text{meas}}$ |
|---|---|---|---|---|---|
| 0.5 mm | 442.04 m/s | 862.85 m/s | 885,97 m/s | 50.89° | 51.1° |
| 0.8 mm | 556.39 m/s | 1081.39 m/s | 1082,08 m/s | 38.06° | 38.0° |
| 1.0 mm | 620.43 m/s | 1198.2 m/s | 1090,00 m/s | 33.56° | 34.0° |

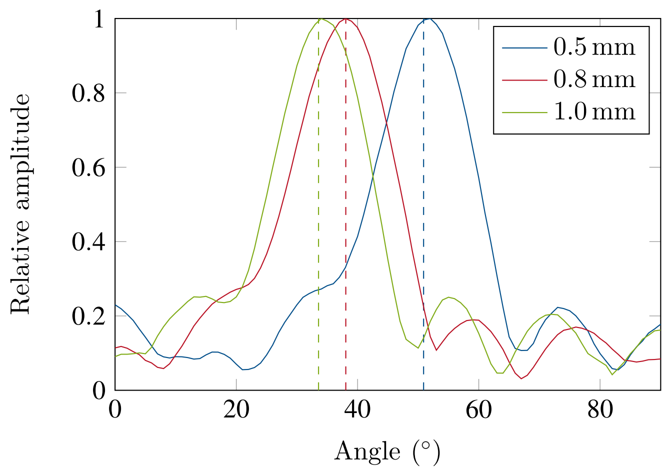


Fig. 5. Received amplitude as function of angle of incident, normalized to each maximum for three specimen thicknesses. All three maxima show good agreement to the calculated values (dotted) (Table I). Next to the global maxima, there are several local maxima, caused by the directivity pattern of the ultrasound array.

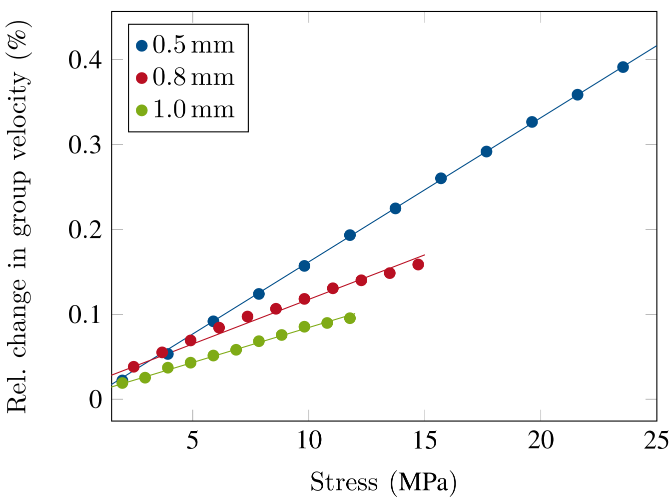


Fig. 6. Relative change of group velocity as function of mechanical stress for three specimen of steel of different thicknesses. All three measurements series show a close to linear relationship for the measured stress range. The maximum stress is different for these samples as the maximum force applicable by the experimental setup is limited.

Applying tensile stress to the steel sheet causes a slight increase in group velocity, up to 0.39 % for the sheet of 0.5 mm at a stress of 23.54 MPa. All three series show a good agreement to a linear fit (Fig. 6) for an applied force of up to 1177 N.

## V. Conclusion

Our experiment proves that exciting Lamb waves for different material thicknesses, and, thus different coupling angles using the same, electronically steerable phased-array is feasible. Additionally, using a reverse approach of sweeping the angle and obtaining the material thickness if the material properties are known, is possible as well. The experiments are robust as the signal is strong enough to be received using a low-cost microphone without any additional amplifier (excellent SNR). This allows more challenging setups such as larger distances between the array and the specimen. Two examples where this is interesting are continuously moving assembly lines where testing equipment is mounted outside of the clearance outline of a conveyor belt or production lines where harsh environment conditions may damage in-contact transducers, such as high temperature or reactive compounds. The tensile-test experiment is a demonstration of a simple contactless NDT application using an air-coupled ultrasound phased array. This is not far from a real world scenario, as it resembles the integral measurement of tensile stress in beams. Further experiments planned will include the detection of defects, in other, more challenging materials such as synthetic materials, fibre-reinforced plastics or ceramics. Additionally, utilizing the azimuth steering direction of the array allows the excitation of Lamb waves on curved surfaces, matching the optimal coupling angle in two dimensions or the localized excitation of Lamb waves, allowing the localization of defects.

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