Air coupled ultrasonic defect detection in polymer pipes

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Abstract

Ultrasonic, non-contact defect detection for polymer pipes can provide an easy and reliable method to establish on site quality control without destructive mechanical testing and finally may help to prevent damage from leaking pipes.

The target is to inspect thin walled polymer pipes made of PVDF and PP with small defects in the pipe wall. Air coupled transducers with a nominal frequency of 200 kHz are used to excite Lamb waves in the pipe wall that interact with potential defects. A reference measurement on a flawless part of the pipe helps to mitigate the effects of geometrical and material inhomogeneities.

The possibility to excite only the A_0 Lamb wave mode in thin plates and pipes using air coupled transducers is shown. Defects attenuate the propagating Lamb waves, resulting in a characteristic pattern in the receiver signal. Simulations on the Lamb wave propagation help to identify the dispersion parameters and allow to understand the effect of defects better. The detection of defects is challenging because of other imperfections in the specimen. With a reference measurement the detection of defects down to a size of 1 mm is possible.

Keywords: air-coupled ultrasound, non-contact, guided waves, Lamb wave, polymer pipes

1. Introduction

Defect detection in pipes has a great potential to prevent leaks and severe damage. Ultrasonic inspection as a non destructive testing method allows pipe wall inspection locally and is a promising technique because of its high sensitivity for small cracks. Traditionally liquid coupled ultrasonic (LCUS) involves a coupling medium to guarantee a good connection between transmitter, material and receiver. Air coupled ultrasonics

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(ACUS) inspection does not rely on any coupling agent and allows a contactless examination of pipes [1].

The application scenario of the air coupled ultrasonic inspection of pipes is defect detection, including cracks, production inhomogeneities as voids and the inspection of welds. All these defects have in common that they can only with huge effort be produced artificially. As a starting point, rather large through thickness
10 holes were chosen to test the performance of this inspection method.

Because of the large difference of the acoustic impedance in air and polymers a large part of the emitted signal is reflected at the specimen surface and prevents a classical pulse-echo setup with a single probe. In thin walled structures as pipe walls it is possible to excite a Lamb wave with an air coupled transmitter. The Lamb wave propagates in direction of the long axis of the pipe, interacts with defects along the way and
15 can be detected with an air coupled receiver. This single sided pitch-catch setup avoids the problem that the large signal from the surface reflection masks echos from defects inside the material.

Lamb waves were first described by Horace Lamb more than 100 years ago. The governing equations for anti-symmetric (1) and symmetric (2) Lamb wave modes are presented by Rose [2]:

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(q^2 - k^2)^2}{4k^2pq} \quad (1)$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{(q^2 - k^2)^2} \quad (2)$$

$$p^2 = \frac{\omega^2}{c_1^2} - k^2, q^2 = \frac{\omega^2}{c_2^2} - k^2 \quad (3)$$

where h is the plate thickness, c_1 and c_2 are the wave speeds in the bulk and therefore material parameters, k is the wavenumber and ω is the angular frequency. From the numerical solutions of these equations the phase and group velocity for each propagating mode can be calculated. The Matlab Lamb toolbox [3] provides the possibility to calculate the dispersion relations from the bulk material parameters for the ideal
25 case of a semi-infinite thin plate. Hartmann and Jarzynski and Christman characterized PVDF, PP and PMMA [4, 5]. While non contact testing provides a major advantage, the transition of the pressure wave into the structure is a big challenge. Anti-symmetric modes are easier to excite with a single-sided setup than symmetric modes. The efficiency of the coupling is depending on the transducer angle and on the excited

Lamb mode. The sensitivity of the excitation of a specific Lamb mode with regards to the transducer angle
 30 is investigated.

Leutenegger [6] investigated the non-destructive testing of metal tubes using a laser vibrometer. The air coupled technique in our setup allows a more compact setup and does not rely on reflective tape on the specimen surface, but lacks the information about the direction of the surface displacement.

The Lamb waves that propagate along the pipe wall interact with defects inside the wall. The waves are
 35 reflected or scattered by the defects or mode conversion can take place. Our transmission inspection setup can only detect the attenuation of the A_0 Lamb wave that is caused by the defects. The scattering pattern for Lamb waves at delaminations is investigated by Veidt [7]. Hinders [8] and Fromme [9] investigated the scattering properties in plates of an incoming Lamb wave at through holes with sizes around 10 mm. Using air coupled transducers with a setup very similar to ours, Padiyar [10] examined delaminations in the range
 40 of 10-30 mm in composites.

Mode conversion at asymmetrical defects are investigated experimentally and theoretically by Benmed-
 dour [11]. Ramadas [12] studied mode conversions of the incident A_0 Lamb wave mode at delamination boundaries with air coupled transducers. Our setup does not allow to generate or detect S_0 or higher Lamb modes, therefore the detection of defects using mode converted Lamb waves is not possible.

45 Quaegebeur [13] investigated the quality control of cardboard tubes using air coupled ultrasonic inspection and reported the detection of thickness variations and a decrease of the Young's modulus in the pipe wall.

2. Material and methods

2.1. Specimen

In total six pipes were prepared for testing, three polyvinylidene difluoride (PVDF) and three polypropy-
 50 lene (PP) specimens with different diameters and wall thicknesses according to common standards as shown in Table 1. All pipe samples are 400 mm long and contain four through thickness holes as artificial defects in one cross sectional plane in the middle of the pipe. The sizes of the holes are 0.5 mm, 1 mm, 2 mm and 4 mm to include at least one hole that is almost impossible to detect and one hole that is detected with certainty. The holes are distributed along the circumference with 90° spacing with respect to each other.

Material	Type	Diameter	Wall Thickness
PP	Pipe	110 mm	10.4 mm
PP	Pipe	63 mm	6.0 mm
PP	Pipe	40 mm	3.8 mm
PVDF	Pipe	110 mm	3.7 mm
PVDF	Pipe	63 mm	3.2 mm
PVDF	Pipe	40 mm	2.6 mm

Material	Type	Size (L, W, Th)
PMMA	Plate	$300 \times 100 \times 3 \text{ mm}^3$

Table 1: List of specimens and dimensions: three PP pipes, three PVDF pipes and one PMMA plate.

Material	ρ [kg/m ³]	c_1 [m/s]	c_2 [m/s]
PP [4]	913	2650	1300
PVDF [4]	1779	1930	775
PMMA [5]	1183	2746	1392
Air	1.195	343	-

Table 2: Literature material parameters: density (ρ) and the bulk wave speeds c_1 and c_2 .

For the inspection of the excitation dependency of the Lamb modes on the transducer angle a polymethylmethacrylate (PMMA) plate with a length of 300 mm and a width of 100 mm is used. This material features a low acoustic attenuation. The simple, flat plate geometry facilitates the alignment of the transducers and the variation of the transducers angles.

The bulk material parameters are important, especially for the numerical calculations, but also for the preparation of the setup. Density ρ and the bulk wave speeds c_1 and c_2 are the key parameters for the Lamb wave propagation and are taken from literature as shown in Table 2. Measurements of the longitudinal wave speed on our specimen confirm the material parameters.

2.2. Transmission inspection of thin walled polymer structures

The inspection of thin walled polymer pipes with air coupled transducers imposes special restrictions to the setup. Because these polymers feature a high attenuation for sound waves in general and also for Lamb waves, long range inspection is not suitable. Therefore the transmitter and receiver have to be positioned quite close to each other to minimize the distance d_{Lamb} . At the same time, the relatively low Lamb wave velocity in polymers in the range of two to three times the speed of sound in air gives only a small time frame in which the Lamb wave signal can be detected at the receiver before the direct signal through the air

Figure 1: Setup for ACUS transmission inspection of thin walled structures. The inspection wave travels as pressure wave in air (d_{air}), as Lamb wave in the pipe wall (d_{Lamb}) where it interacts with possible defects and again as pressure wave back to the receiver (d_{air}). The transducer angles α_{Tx} and α_{Rx} can be adapted to the specific material requirements. An optional sound blocker is added to suppress direct signals for the inspection of PVDF specimen. The active diameter of the receiver (12.5 mm) is half the size of the transmitter (25 mm).

arrives. This signal is typically several magnitudes stronger and can mask all usefull signals. As a result, a transmission inspection setup is used with transmitter, a receiver and sometimes a sound blocker being aligned in one plane along the longitudinal axis of the pipe as shown in Figure 1.

Two circular air coupled transducers operating at a nominal frequency of 200 kHz from Ultrasonics (The Ultrasonics Group Inc., State College, PA, USA) are used, one with an active diameter of 25 mm as transmitter and one with 12.5 mm diameter as receiver. While the configuration with two smaller (12.5 mm diameter) transducers does not yield a sufficient signal to noise ratio, using a larger (25 mm diameter) transducer to excite a strong Lamb wave and a higher resolution 12.5 mm diameter receiver to record the signal provides the best setup. Both are mounted on goniometers to adapt to an insonification angle matching the requirements of the specific specimen.

The ultrasonic wave excited by the transducer is a pressure wave in air with a nominal frequency of 200 kHz, resulting in a wavelength of 1.7 mm for a speed of sound in air of 343 m/s. Both, transmitter and receiver are positioned as close to the specimen surface as possible as indicated with d_S in Figure 1. This also means that the specimen surface is in the near field of the transmitter sound field. Due to the slightly non circular geometry of the pipe, this distance changes from close to 0 mm to 3 mm while scanning around a pipe. When the pressure wave hits the surface of the specimen, a Lamb wave in the pipe wall is excited. For maximum

Specimen	Mode	α_{Tx}, α_{Rx}
PP Pipe	A_0	19°
PVDF Pipe	A_0	29°
PMMA Plate	A_0	19°
PMMA Plate	S_0	9°

Table 3: Transducer angles for different materials and a frequency of 200 kHz.

transition of the wave at the air-structure interface, the projected k-vectors of the wave in the air (k_{air}) and in the plate (k_{Lamb}) have to match:

$$k_{air} * \sin(\alpha_{Tx}) = k_{Lamb} \quad (4)$$

From Equation 4 one can calculate the required insonification angle α_{Tx} . The angles for the measurements are specified in Table 3 for each material and a transducer frequency of 200 kHz.

The A_0 Lamb wave inside the pipe wall has a wavelength in the range of 3.3-3.5 mm for PVDF and 5.5-6.0 mm for PP. As Lamb waves feature particle motion over the whole cross-section of the structure, the wave will interact with any defect regardless of its position in depth inside the pipe wall. The propagating Lamb waves also radiate into the surrounding air, allowing a detection with the receiving transducer.

A typical excitation signal for this setup consists of three periods of a sine wave windowed by a Gaussian window. This signal is then amplified up to 400 V by a Ritec RPR-4000 pulser/receiver (RITEC Inc., Warwick, RI, USA) to drive the transmitter. The use of a continuous excitation signal is not possible because the direct air signal would overlay the Lamb wave signal at the detector.

The received signal is amplified by 40 dB with a preamplifier and then by another 30 dB by the amplifier and digitized with 100 MHz. The typical range of the signal is 30 mV_{pp}. Up to 256 averages are taken to improve the signal to noise ratio.

2.3. Lamb wave mode excitation and detection in polymer plates

The goal of this experiment is to show the dependency of the excitation and detection of different Lamb modes with respect to the transmitter and receiver angle, especially the excitation of a pure A_0 Lamb wave. PVDF and PP do not allow this type of investigation due to the high damping factor that does not allow the detection of modes other than the A_0 Lamb mode. The experiments are therefore carried out with a PMMA plate.

Figure 2: Setup for A_0 and S_0 Lamb mode excitation and detection. The absolute transmitter angle can be varied over selected angles and the absolute receiver angle can be varied from 0° to 20° for each transmitter angle.

The absolute transmitter angle α_{Tx} is varied from 0° to 20° and receiver angle α_{Rx} are varied for every transmitter angle in the same range as shown in Figure 2 and the change of the transmitted signal is investigated.

110 2.4. Lamb wave velocity measurement

To verify the dispersion relations calculated in numerical simulations, phase and group velocity are measured experimentally. Therefore the transmitter-receiver distance is increased by moving the receiver by 10 mm in steps of 0.1 mm as shown in Figure 2. With the inspection frequency f being fixed by the transducers, the pipe thickness d is the only parameter that can be varied, resulting in only a small number
115 of measurement points on the dispersion curve.

2.5. Circumferential pipe inspection

To identify flaws in the pipe wall, an inspection technique is required that allows to scan along the circumferential pipe direction. This can either be done by turning the pipe and keeping the transducers fixed or by moving the transducers around the pipe. To increase the flexibility with regards to the pipe
120 diameter, a setup with a pipe rotating on wheels is chosen and transmitter and receiver are fixed above the pipe as shown in Figure 1.

PVDF pipes require an additional sound barrier between transmitter and receiver because the low Lamb wave speed results in the arrival of the Lamb wave signal at about the same time as the direct wave through the air which needs to be blocked. Two large rectangular sheets of thick paper with a spacing of 5 mm to

Figure 3: Setup for ACUS reference measurement of pipes. Transmitter and receiver are shifted together by 50 mm to a flawless position on the pipe.

each other that touch the pipe surface at the topmost position turned out to provide the best results.

2.6. Setup for reference inspection

Since geometrical and mechanical inhomogeneities have a big influence on the measured signal from Lamb waves, a reference measurement helps to improve the flaw detection rate. Therefore the transducers are shifted about ~ 50 mm along the longitudinal axis of the pipe to an undamaged region, keeping the transducers distance constant. A second scan is performed as reference measurement with exactly the same parameters as shown in Figure 3.

2.7. Signal Analysis

Figure 9a shows a typical B-Scan for a complete scan around a 110 mm diameter PVDF pipe and some overlap, leading to more than 400° scanning range on the x-axis. The amplitude of the A_0 Lamb wave is color coded and in the range of 0-30 mV_{pp}. The chosen time frame on the y-axis shows only the Lamb wave. Before the Lamb wave no relevant signal is present and the direct air waves which arrive later have a much higher amplitude.

One can immediately notice the variation of the Lamb wave arrival time with the position. This delay is caused by either local changes in the pipe wall which lead to a change of the Lamb wave velocity or by the out-of-roundness of the pipe that causes a change in the transducer to pipe surface distance and therefore also alters the total travel time of the ultrasonic wave.

An evaluation window is chosen that is shifting with the Lamb wave delay as shown in Figure 9a to avoid

having the influence of these geometrical effects in the evaluated signal.

The root mean square (RMS) value of the signal within the window is chosen as evaluation function for every single measurement point.

3. Numerical Calculations

3.1. Lamb wave propagation simulation

Proper knowledge of Lamb wave propagation parameters is a prerequisite for the preparation of the experimental setup, especially for the determination of the transducers angles. The Matlab Lamb toolbox [3] solves the dispersion relations for symmetric and anti-symmetric Lamb waves numerically for the wave number k , assuming a thin plate (infinite in two dimensions, finite in thickness direction) surrounded by air. The parameters for air are the density ρ_{air} and sound speed c_L . Inside the plate the parameters are density ρ and either Young's modulus E and Poisson's ratio ν or the bulk wave speeds c_1 and c_2 as shown in Table 2. According to the transducer frequency of 200 kHz and the plate thickness ranging from 2.6 mm to 3.7 mm for PVDF and from 3.8 mm to 10.4 mm for PP, the numerical search range for $f \cdot d$ is 150-1350 kHz · mm for PVDF and 75-2200 kHz · mm for PP, respectively. The phase velocity search space is limited to 400-1500 m/s for PVDF and to 500-2500 m/s for PP. From the wave number k the phase and group velocities as well as the incident angles are calculated. The results for PVDF are shown in Figure 7 and for PP in Figure 8.

3.2. Simulation of defects

To illustrate the signal shape that a defect in the pipe wall causes in the measured data, a numerical model is set up. The model geometry is shown in Figure 4a. In contrast to the experiment, this model uses a flat plate with periodic boundary conditions instead of a curved pipe and a 2D flat defect instead of a round through hole. In the center of the plate a planar defect is located. The defect goes through the complete thickness of the plate, has a specific length in the short direction of the plate (4 mm, 2 mm, 1 mm or 0.5 mm), and does not extend in the long direction of the plate. The paths along which receiver and transmitter are moving in the experiment are indicated in Figure 4a. The incident plane wave consists of a sine wave windowed by a Gaussian window similar to the experimental setup. This wave is propagated forward numerically from the initial position to the defect position with the dispersion parameters of the A_0

a)

b)

c)

Figure 4: Interaction of Lamb waves in periodic PVDF plates with defects. Diffraction pattern resulting from a plane wave interacting with a 1 mm plane defect in the center of the specimen at position (0,0): contour lines (b) of the wave amplitude in an area as shown in (a), wave amplitude (c) for a receiver positioned 15 mm away from the defect as drawn in black in (b).

a)

b)

Figure 5: Transducer angle dependency of air coupled A_0 (blue, top) and S_0 (red, bottom) Lamb wave excitation and detection in PMMA plates.

The A_0 Lamb wave mode is depicted for an excitation with a transmitter angle of 19° (solid blue line) and 9° (dotted blue line). The receiver signal level is shown for a receiver angle from 0° to 24° .

The S_0 Lamb wave mode is shown for an excitation with a transmitter angle of 9° (solid red line) and 19° (dotted red line).

Lamb wave calculated using the Lamb toolbox. The propagation kernel according to Rastogi [14] is used.

At the defect location the wave amplitude is set to zero which is equivalent to no transition of the wave through the defect. The wave is then propagated further and the resulting diffraction pattern in the area behind the defect is shown in Figure 4b. Experimentally, the receiver is not scanning along both, long and short directions of the plate but is only moved along the short direction of the plate at a fixed distance of 15 mm to the defect. The resulting signal along this path (black in Figure 4a and 4b) is shown in Figure 4c.

4. Results

4.1. Lamb wave mode excitation and detection in thin polymer plates

For air coupled ultrasonic setups, the transducer angle is of major importance to excite and detect a specific Lamb wave mode. Figure 5a shows the measured signal amplitude for the A_0 Lamb waves for two transmitter angles α_1 and α_2 as a function of the receiver angle. Figure 5b shows the same results for S_0 Lamb waves.

With transmitter and receiver angle matching the optimal A_0 angle ($\alpha_{T_x} = \alpha_{R_x} = \alpha_2$), the best transmission ratio is achieved (blue cross). This result is expected, as an one sided anti-symmetric excitation prefers the anti-symmetric Lamb modes where the out of plane particle motion is going in the same direction throughout one cross section.

Setting the transmitter and receiver angle to the optimal S_0 angle ($\alpha_{T_x} = \alpha_{R_x} = \alpha_1$) yields a transmission ratio that is 13 dB less than the one for the A_0 mode (red circle).

An A_0 Lamb wave is also generated as a byproduct when the S_0 wave is excited with the optimal S_0 angle α_1 . This is shown as a blue dotted line in Figure 5a and the signal amplitude is 15 dB (blue triangle) lower than for the A_0 wave.

Similarly also a S_0 Lamb wave can be detected when the A_0 wave is excited which is shown as red dotted line in Figure 5b. This signal is 30 dB lower than the A_0 signal (red diamond).

For the 3 mm thick PMMA plate used in the experiments, the optimal S_0 and A_0 transducer angles α_1 and α_2 are determined to be 9° and 19° .

In general the excitation behavior is not very sensitive to small changes of the transducer angle as the peaks in the blue and red curves in Figure 5 are quite broad (-0.2 dB for a change in angle of 1°).

One can conclude that it is possible to excite an almost pure A_0 Lamb wave in a plate with air coupled transducers which is important for defect detection in general and the detection of potential A_0 to S_0 mode conversions at defects.

4.2. Lamb wave velocity measurements

Experimentally only the A_0 Lamb mode propagation parameters could be measured in PVDF and PP pipes because of the high acoustic damping in these polymers.

a)

b)

Figure 6: Phase velocity (6a) and group velocity (6b) measurement for a PVDF pipe with 3.5 mm thick walls.

The phase velocity is calculated by tracking the maximum of the highest peak with increasing relative transmitter-receiver distance, shown as black line in Figure 6a for a single measurement on a PVDF pipe with 3.5 mm wall thickness. The group velocity is calculated by tracking the peak of the signal envelope with increasing distance, shown in Figure 6b. Several hundred measurements were taken around the circumference of each pipe specimen for averaging.

Figure 7 shows the calculated group and phase velocity of the A_0 , S_0 and A_1 Lamb wave mode for PVDF as lines and the measured values for the A_0 mode at three specific $f \cdot d$ values as crosses. The measured values are all slightly (4%) higher than the calculated ones. Figure 8 shows the group and phase velocity for PP, again calculated values as curves and the measurements as crosses. In this case, the simulated results are about 10% too high. Possible explanations for the differences are discussed in Section 5.1.

The results show that the Matlab Lamb toolbox provides a way to get the dispersion relation from material parameters also for polymer pipes and the pipe curvature is negligible in the investigated range. Therefore the measured and the computed values for the wavenumber k and the derived group- and phase velocity can

Figure 7: Dispersion Relation for PVDF. Simulated results for plates, measured data for pipes.

be used to prepare the settings of the experiment. With k one can calculate the transmitter and receiver angles from equation 4. The group velocity helps to determine the distance d_{Lamb} shown in figure 1 to make sure that the time window is large enough to capture the Lamb waves before the direct air signal arrives. In general, knowing the dispersion relation for the different pulses in the acquired signal allows identifying them as specific Lamb modes.

Additionally, simulations provide a much broader range of frequency values and also include the S_0 and other higher Lamb wave modes that may not be possible to be acquired experimentally.

From the measured data, the total attenuation of the A_0 Lamb wave signal is determined to be in the range of -5 dB/cm for both PVDF and PP pipes. This contains both, inherent damping by the polymers as well as damping of the Lamb wave by radiation into the air and beam divergence.

4.3. Circumferential pipe inspection

When scanning the pipe for defects along the circumference, a defect creates a typical signature in the RMS value of the Lamb wave signal. For a receiver diameter of 12.5 mm, this signature has the shape of

Figure 8: Dispersion Relation for PP. Simulated results for plates, measured data for pipes.

a "W" with two outer peaks and the middle peak at the center of the defect as seen in the blue curve in Figure 9b. For transducers of diameter 25 mm, the inner peak is missing.

Generally, the noise level in the signal is around 0.5 dB with the main source being the electrical equipment as motors or power supplies.

The evaluated signal varies for one scan around a specimen by as much as 6 dB without any defects, mainly due to material inhomogeneities of the specimen and geometrical imperfections, depending heavily on the setup. Major factors are thickness variation, elliptical shape of the pipe and inhomogeneities in the pipe wall from the extrusion process. These effects make the detection of small defects a lot more difficult. While many aspects of the setup geometry may influence the results of air coupled ultrasonic inspection techniques it is difficult to separate them in the chosen setup with non-perfect pipes. Ramadas [15] shows the influence of the transducer misalignment for air coupled transducers in the ideal case of a plate geometry.

Figure 9: (a) B-Scan of about 450° of a 110 mm PVDF pipe specimen with artificial defects with the evaluation window (red) that is adapting to the Lamb wave delay and allows to evaluate the signal amplitude. Root mean square value (b) of the signal in the evaluation window at the defect position in blue and at the reference position in red. Figure c shows the difference of both evaluations. The impact of the 4 mm, 2 mm and 1 mm defects is visible and the signal is almost constant otherwise. The probes for the reference measurement were moved in longitudinal direction of the pipe as shown in figure 3.

a)

b)

Figure 10: (a) Results for an inspection of a 110 mm PP pipe and the amplitude drop for the 4 mm defect in blue. (b) Results for a 40 mm PP pipe for comparison. Note that the circumferential resolution (in mm) is the same for both measurements and therefore the number of measurement points is higher for the 110 mm PP pipe.

a)

b)

Figure 11: Drop of the signal amplitude for different defect sizes in PP (a) and PVDF (b). Simulations were carried out for defects from 0 mm to 4 mm in small steps and are shown as connected lines. Measurements were conducted with 1 mm, 2 mm and 4 mm defects and are shown with crosses.

4.4. Detection limit improvement with reference measurement

The reference measurement shown as red line in Figure 9b allows to reduce the influence of the local inhomogeneities of the pipe on the defect detection. When subtracting the signal at the defect position from the reference measurement, one is left with a constant signal in non-damaged parts of the pipe and the signature of the different defects. In comparison with the original signal shown in blue in Figure 9b, the "W" shape of the defects in the enhanced measurement in Figure 9c is quite similar to the signal that is expected based on the numerical calculations shown in Figure 4c and also similar to the signal shape for defects in plate specimen (Neuenschwander et al[16]).

In PVDF, the 4 mm, 2 mm and 1 mm diameter defects can successfully be detected as shown in Figure 9b and for PP the same result is true as seen in Figure 10. The 0.5 mm defect could not be detected in any sample.

It is also possible to show the influence of the defect size on the amplitude drop (peak to peak as shown in blue in Figure 10). In Figure 11a the measured (crosses) and simulated (lines) effects of a defect are shown for PP. The amplitude drop increases with increasing defect diameter as well as with decreasing wall size. The results from the numerical model suggest a linear relation and the experimental results are in line with the simulation but the low number of samples does not allow further statements on the relation of defect size and amplitude drop. For PVDF the results are shown in Figure 11b and follow the same trend as for PP but the amplitude drop is in general a bit higher.

5. Discussion

Inspections of PVDF pipes were possible only with the help of a sound blocker that prevents direct transmission of the ultrasonic wave through the air. The additional time frame that is gained with a sound blocker is only a few microseconds, afterwards sound waves arrive at the transducer that are reflected at various other surfaces, e.g. the pipe wall. Since the sound blocker is touching a part of the pipe surface that is examined, the Lamb waves might be damped and it cannot be excluded that mode conversions occur.

The transducers are mounted as close to the specimen surface as possible as indicated with d in Figure 1. This also means that the natural focal point (47 mm for transducers with 25 mm active diameter) at the

Figure 12: Measured sound field of a 25 mm Ultrasonic transducer in lateral (left) and frontal (right) view.

transition from near to far field is not at the pipe surface. Experimentally, this configuration resulted in a better signal transmission. On the downside one is operating in the near field of the Ultrasonic air coupled transducers that shows some inhomogeneities over the cross section as it can be seen in Figure 12. Because of its slightly elliptical shape, the pipe does not turn perfectly on the supporting wheels. Therefore, the pipe surface to transducer distance d varies during circumferential pipe inspection.

This leads to a variation of the Lamb wave propagation path because the path in the air (d_{air}) increases for an increasing distance d_S and the path in the pipe (d_{Lamb}) decreases thus leading to a longer travel time of the wave. This effect is superimposed with material parameters that may change locally along the circumference of the pipe and alter the Lamb wave velocity and therefore affect the total travel time. Both effects can not easily be separated with the current setup.

5.1. Numerical wave propagation

The simulations for the effect of defects give a good prediction on the signal shape and also show the same trend as the measurements. However, as expected for a simplified model, the absolute values differ slightly. Several effects of the propagation model may contribute to this effect. First of all, the geometry is

Figure 13: Pipe optimal insonification angle for A_0 Lamb mode in a 110 mm PVDF pipe calculated from the measured real wall thickness.

modelled as a plate with a plane wave propagating, whereas in reality the wave is originating from the spot where it is excited on the round pipe surface and then propagates in the curved pipe wall. The experiments show that for the given pipe diameters, wall thicknesses and curvatures the plate model is sufficient. Second, the defects are modelled as planar defects instead of three dimensional holes. The simplified, flat defect is not causing significant changes to the diffraction pattern behind the defect. For the part of the signal that is reflected back at the defect surface in the direction of the transmitter, a major difference would exist between the round shape of the through hole and the flat defect, but this signal is not considered for this setup. Third the reradiation of the Lamb wave into air and the detection with the transducer is not modelled.

For more complex models finite element methods may be more suitable.

Additionally to the linear dependency of the amplitude on the defect size, the signal width (left peak to right peak) changes with the defect size as it gets narrower for bigger hole diameters.

5.2. Effect of pipe imperfections

The large variability in circumferential direction is mainly a combination of the change in the pipe wall geometry and material along the circumference (wall thickness, density) and the geometry of the setup (slightly non circular pipe and the probe distance to the specimen surface). The pipes seem to be more homogeneous in longitudinal direction, which is reasonable because of the extrusion process during manufacturing. To assess the geometry of the pipe specimen, X-ray computed tomography measurements of each pipe were examined. Based on the pipe wall thickness determination from computed tomography data and assuming a constant density distribution over the pipe circumference, the optimal insonification angle for

the A_0 Lamb waves can be calculated from the data gained from the Lamb toolbox simulations. As it can be seen in Figure 13, the total variation of the optimal angle for a total thickness variation of 0.25 mm is less than 0.2° and therefore rather small. Considering the experimental results for the sensitivity of the Lamb wave transmission level as shown in Figure 5 for PMMA, such small angle variations should not have a major impact on the measured signal.

6. Conclusion

It is possible to detect artificial defects using air coupled ultrasonic inspection in thin polymer pipe walls. When scanning a pipe with a single-sided pitch-catch setup, defects create a characteristic pattern in the gathered data. For our application the knowledge of the pattern facilitated detection of defects as small as 1 mm. A simple numerical model confirms the experimental results.

The pipe samples are all within the tolerances for wall thickness and diameter according to the standards for PVDF and PP. However small variations in pipe geometry and material present a big challenge for examination with the chosen setup because the relevant acoustic parameters vary significantly and these effects are superposed with the defect signals. It is challenging to separate defects from normal variation in the measured signal. A reference measurement of a flawless part of the pipe close to the defects has proven to be a reliable method to mitigate most of the unwanted effects.

Future work on the effect of defects, especially an improved model and potentially more experimental data for validation may open the possibility to not only detect defects but also quantify the defect size or separate between different defect types.

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