Numerical Investigation of Air-Coupled Generation of Lamb Waves Using Rectangular Phased Arrays

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Abstract. In the case of non-destructive testing and evaluation (NDT & NDE) of plate structures ultrasonic Lamb waves are used. Very often air-coupled ultrasonic transducers are used for non-contact Lamb wave excitation and reception. This method has a very serious drawback: global insertion losses for an air-coupled system may be 120–160dB typically, so optimum vibration excitation in tested material is needed. A numerical investigation has been performed in order to evaluate air-coupled Lamb wave excitation in an isotropic single layer plastic film using square transducer. A new method of excitation using planar phased arrays with rectangular elements has been proposed.

1. Introduction

Many ultrasonic NDT methods use couplants between the material under a test and ultrasonic transducers. However there are certain cases where it is not possible, because the tested material may be damaged or contaminated by a couplant, for example paper, plastic and composite materials.

It is not a new idea in NDT to use non-contactly without couplant generated Lamb waves (or guided waves) for testing of plate materials. Different techniques are used, for example lasers [1, 2], EMATs (Electro-Magnetic Acoustic Transducers) [3], electrostatic excitation methods [2]. Air-coupled generation of Lamb waves in plate materials is becoming the most popular method in NDT [4-10]. Popularity of this method still grows up. There is a demand on improvements, and numerical model of entire Lamb wave system is needed. Usually Finite Element Method (FEM) based models are used to calculate Lamb wave propagation in plate structures and Impulse Response Method (IRM) based models are used to calculate acoustic pressure, radiated by air-coupled transducer [9, 10]. Those hybrid models are exact enough, but they still require a lot of computational time and storage for output data.

The objective of this research was to investigate by means of numerical modeling excitation of fundamental A_0 Lamb wave in thin plastic films. These films are flexible and unstable, so quality control can be implemented only by using air-coupled Lamb wave excitation and reception. For modeling a free software tool "The Lamb Matlab toolbox" (Beta version 0.1) was used [11, 12]. The modeling program has been checked and necessary corrections were made, which were needed for simulation of excitation signal generation, calculation of array geometry and visualization of output results. The improved simulation tool has been used to obtain Lamb wave normal displacement signals at selected points on a plate surface.

2. Numerical simulation methods

The acoustic pressure, generated by a rectangular piston in liquid or gas type medium, may be calculated using the Impulse Response Method (IRM) [13-15].

Let us consider a rectangular transducer $2b$ long and $2a\left(a \le b\right)$ wide and located in $z_0 = xy0$ plane (Figure 1(a)).

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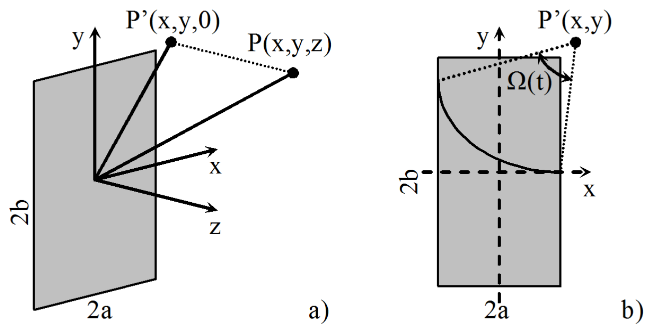

Figure 1. Geometry and coordinate system for calculation of the impulse response of a rectangular transducer.

The impulse response function h depends on time t, spatial coordinates of the point $P(x,y,z)$, where this function is calculated, the sound velocity c in a medium, the obliquity factor $\beta(z,t)$ corresponding to the transducer boundary conditions and the angle $\Omega(P',t)$, subtended at the point P' (Figure 1(b)) by the arc, as in equation (1):

$$h(P,t) = c \cdot \frac{\beta(z,t)}{4\pi} \cdot \Omega(P',t) \tag{1}$$

The obliquity factors $\beta(z,t)$ are given in the time domain, as in equation (2):

$$\beta(z,t) = \begin{cases} 2 & \text{rigid baffle,} \\ 2z/(ct) & \text{soft baffle,} \\ 1+[z/ct] & \text{free field.} \end{cases} \tag{2}$$

When the transducer vibrates at the velocity $v(t)$ in a liquid or gas type medium with the density ρ, then the transient pressure $p(P,t)$ at the point $P(x,y,z)$ is calculated using convolution operation (*), as in equation (3):

$$p(P,t) = \rho \frac{\partial v(t)}{\partial t} * h(P,t) \tag{3}$$

In the case of air-coupled transducers the distance dependent attenuation should be estimated. This is done by calculating the attenuated impulse response function $h_a(P,t)$, when the inverse Fourier transform is applied to the calculated impulse response function in the frequency domain $H(i\omega)$, multiplied by the attenuation function $A_{atte}(P,i\omega)$, as in equation (4):

$$h_a(P,t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} A_{atte}(P,i\omega) H(i\omega) d\omega \tag{4}$$

For the calculation of the air attenuation see [11, 16].

If an infinite isotropic film is excited by an incident time harmonic signal, which exerts pressure over a finite radius circular region, then normal displacements in the film can be calculated using the Time Harmonic Solution (THS) method [11, 17]. Because of the THS method complexity we shall not analyze it in more detail. In short, the explained solution assumes that a Continuous Wave (CW) is used. For the transient signal a finite set of harmonic excitation frequencies are used, and normal displacements are obtained by using a harmonic summation method.

In "The Lamb Matlab toolbox" software tool a finite excitation zone is divided into circular sub-regions of radius a. The pressure signal is calculated at the centre point of a circular sub-region and taken equal in all sub-region area. The radius a should be small, at least four times smaller than the minimum Lamb wavelength. Total normal displacement signal at the given point on a film is computed by superposition of normal displacements, created by all circular sub-regions.

3. Numerical investigation

Numerical investigation has been performed simulating air-coupled A_0 Lamb wave mode excitation in a clear polyvinyl chloride (PVC) film. A square transducer *T* and simplified 2D approach were used (Figure 2). Four different PVC thicknesses *d* have been chosen: *d*=1, 0.5, 0.25 and 0.15mm. The A_0 mode phase velocity dispersion curves were calculated using SAFE (Semi Analytical Finite Element) method (Figure 3).

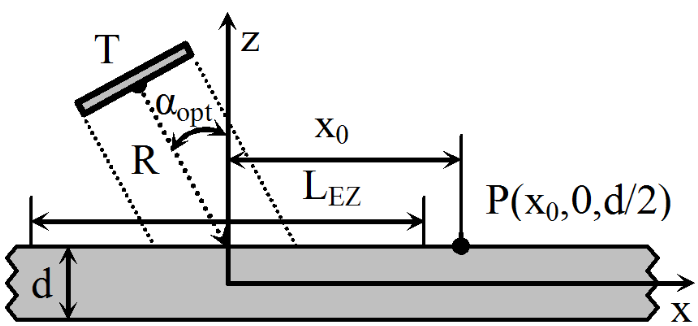

Figure 2. Schematic diagram of air-coupled Lamb wave excitation using transducer *T*.

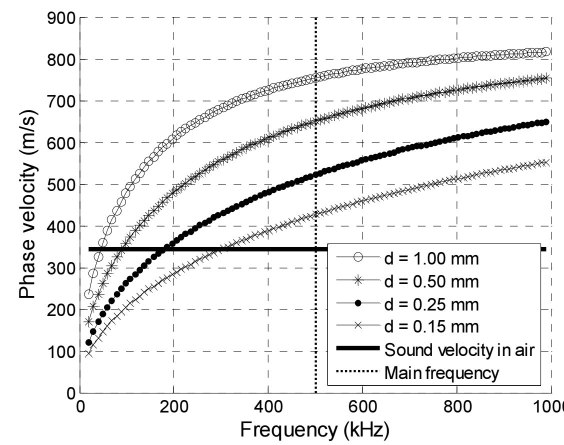

Figure 3. Phase velocity dispersion curves for A_0 mode in clear PVC films of thickness *d*.

Optimum incidence angle α_{opt} is calculated according to the Snell's law, as in equation (5):

$$\alpha_{opt} = \arcsin \frac{V_{Air}}{V_{Lamb}} \tag{5}$$

where V_{Air} is the sound velocity in air, $V_{Air} = 343\text{ms}^{-1}$; V_{Lamb} is the Lamb wave phase velocity. From the Snell's law follows that air-coupled excitation is not feasible for $V_{Lamb} \leq V_{Air}$, so the 500kHz main frequency has been chosen. The calculated optimum incidence angles are shown in Table 1.

Table 1. A_0 mode phase velocities and optimum incidence angles at 500kHz main frequency.

PVC thickness (mm)	A_0 mode phase velocity (ms^{-1})	Optimum incidence angle (°)
1.00	754.6	27.1
0.50	650.4	31.9
0.25	521.8	41.1
0.15	426.6	53.6

The square transducer *T* used for excitation has dimensions $18 \times 18\text{mm}$ and is located at the distance $R = 30\text{mm}$ from the excitation zone centre on the film surface and deflected by the optimum incidence angle α_{opt} (Figure 2). The length of *x*-line type excitation zone is set to $L_{EZ} = 40\text{mm}$, the zone is filled with 201 circular sub-regions of the $a = 0.1mm$ radius. The rigid baffle obliquity factor $\beta(z,t) = 2$ was used in the *T* simulations. The transducer *T* surface radiates a particle velocity signal of 5 cycles harmonic pulse with the sinus type envelope, 500kHz main frequency, 1 ms^{-1} amplitude and 100MHz sampling frequency. The pulse bandwidth has been limited to (303-950)kHz (figure 4).

The normal displacement pulse of the A_0 Lamb wave mode is calculated at the point *P*, situated on the plate's surface at $x_0 = 21\text{mm}$ distance from the excitation zone centre (Figure 5 is for $d = 1.00\text{mm}$ and figure 6 is for $d = 0.15\text{mm}$).

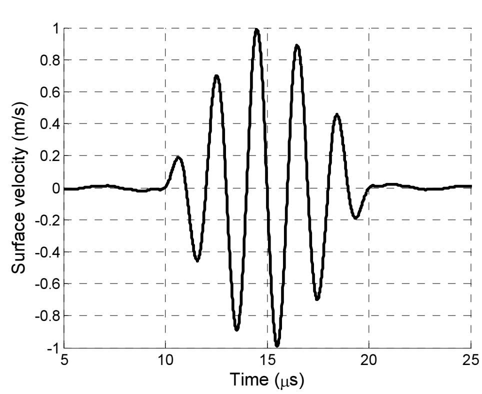

Figure 4. Transducer *T* velocity signal: main frequency 500kHz, bandwidth (303-950)kHz.

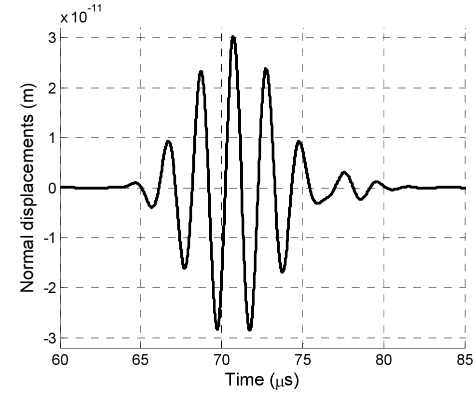

Figure 5. Normal displacements pulse at the point *P* using transducer *T* when *d*=1.00mm.

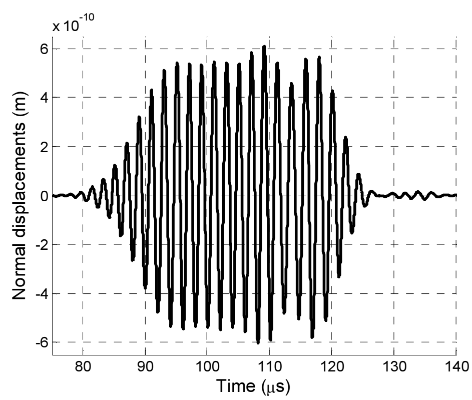

Figure 6. Normal displacements pulse at the point *P* using transducer *T* when *d*=0.15mm.

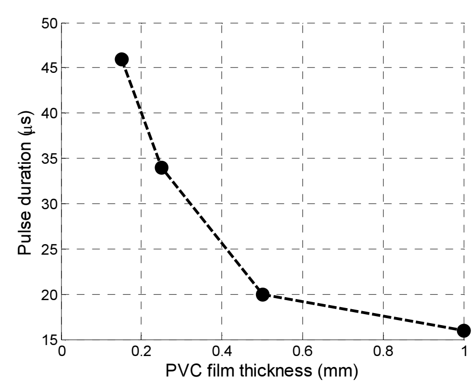

Figure 7. Normal displacements pulse duration dependency versus PVC film thickness *d*.

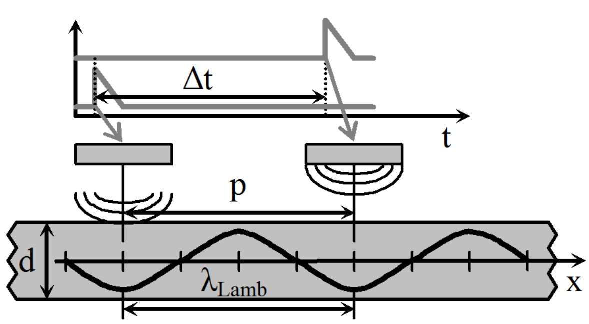

Figure 8. Principle of air-coupled Lamb wave excitation using phased array with rectangular radiators and delayed excitation.

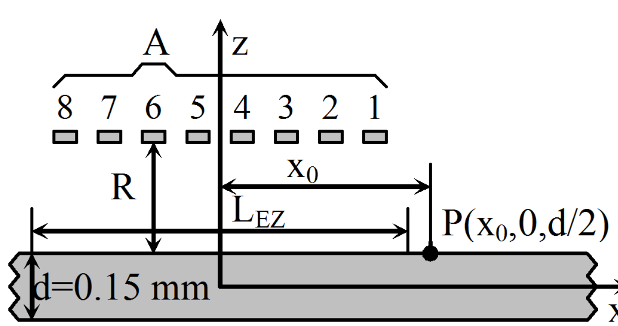

Figure 9. Schematic diagram of air-coupled Lamb wave excitation using phased array *A*.

It was observed, that the pulse duration grows up when the PVC film thickness is decreased (Figure 7).

If there is a demand on excitation of A_0 mode in the case $V_{Lamb} \le V_{Air}$, a new method is proposed. It is based on application of an air-coupled planar phased array with rectangular radiators, were the array pitch p is equal to the Lamb wavelength in a PVC film: $p = \lambda_{Lamb}$ (Figure 8).

By exciting array elements by suitable delayed signals, summation of vibrations in the film is achieved. The delay time Δt is given by equation (6):

$$\Delta t = \frac{\lambda_{Lamb}}{V_{Lamb}} \quad (6)$$

The phased array pitch p and the delay times are determined by A_0 mode phase velocity and wavelength (Figure 10) at the selected frequency. The main frequency of 20kHz has been chosen, where the wavelength of A_0 mode is $\lambda_{Lamb} = 4.7\text{mm}$. The phased array A (figure 9) consists of 8 rectangular elements with dimensions of 2×15mm and 2.7mm space between elements. It is located at the distance $R = 1\text{mm}$ from the excitation zone centre on the film surface. The array A element surface radiates a particle velocity signal of 5 cycles sinus pulse with the sinus type envelope (Figure 11). Impulse of normal displacements at the point P has been calculated for two cases. In the first case (Figure 12) no delays for array elements have been used. In the second case (Figure 13) delay time for each element has been increased by the step $\Delta t = 50.2\mu\text{s}$, calculated according to equation (6).

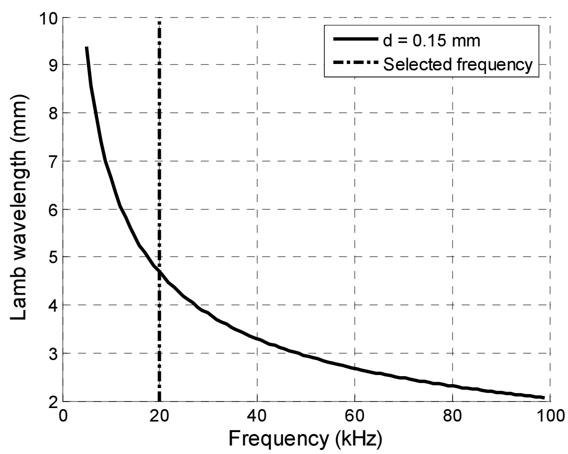

Figure 10. A_0 mode wavelength dependency versus frequency for PVC d=0.15mm.

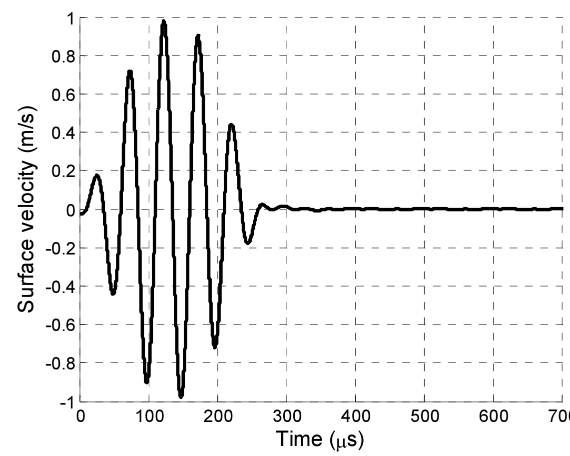

Figure 11. Array element velocity signal: the main frequency 20kHz, the bandwidth (10-30)kHz.

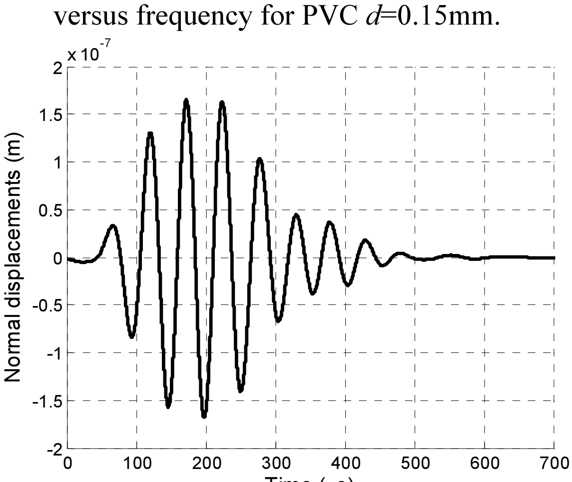

Figure 12. Impulse of normal displacements at the point P; no delays for array A elements.

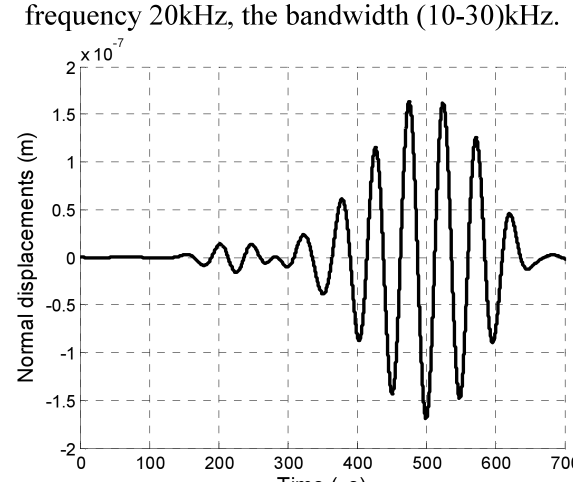

Figure 13. Impulse of normal displacements at the point P; delays between array A elements were used.

4. Conclusions

Air-coupled generation of A_0 Lamb wave mode in clear PVC plastic films has been investigated.

For phase velocities $V_{Lamb} > V_{Air}$ excitation according to the Snell's law is feasible. Simulation showed that decreasing of film thickness increases the duration and the maximum amplitude of A_0 mode impulse.

For phase velocities $V_{Lamb} > V_{Air}$ excitation according to the Snell's law is not feasible. A new method based on application of a planar phased array has been proposed for A_0 mode excitation. Simulation showed that the new method eliminates the effect of significantly increased A_0 mode pulse duration, which has been observed in thin plastic films.

References

[1] Kim D, Cho Y and Lee J 2010 Assessment of wall-thinning in carbon steel pipe by using laser-generated guided wave *Nuclear engineering and technology* **42** 546–51

[2] Wu Y, de Labachelerie M and Bastien F 2002 Investigations on excitation and detection methods for Lamb wave sensors *Sensors and Actuators A* **100** 214–22

[3] Ferrari R M G 2009 The Acoustoelastic Effect: EMAT Excitation and Reception of Lamb Waves in Pre-Stressed Metal Sheets *Proceedings of the COMSOL Conference Milan*

[4] Pettersson T and Anttila J 2002 On the verification of the applicability of the orthotropic plate wave theory to paper *Ultrasonics* **39** 617–22

[5] Kažys R, Demčenko A, Žukauskas E and Mažeika L 2006 Air-coupled ultrasonic investigation of multi-layered composite materials *Ultrasonics* **44** e819–22

[6] Kažys R, Demčenko A, Mažeika L, Šliteris R and Žukauskas E 2007 Air-coupled ultrasonic non-destructive testing of aerospace components *Insight* **49** 195–99

[7] Yañez Y, Garcia-Rodriguez M, Garcia-Hernandez M J, Salazar J, Turo A and Chavez J A 2008 Lamb wave generation with an air-coupled piezoelectric concave array using square-wave burst excitation *NDT&E International* **41** 292–99

[8] Raisutis R, Kazys R, Zukauskas E and Mazeika L 2011 Ultrasonic air-coupled testing of square-shape CFRP composite rods by means of guided waves *NDT&E International* **44** 645–54

[9] Dobie G, Spencer A, Burnham K, Gareth Pierce S, Worden K, Galbraith W and Hayward G 2011 Simulation of ultrasonic lamb wave generation, propagation and detection for a reconfigurable air coupled scanner *Ultrasonics* **51** 258–69

[10] Masmoudi M and Castaings M 2012 Three-dimensional hybrid model for predicting air-coupled generation of guided waves in composite material plates *Ultrasonics* **52** 81–92

[11] Prego-Borges J L 2010 Lamb: a simulation tool for air-coupled Lamb wave based ultrasonic NDE systems Ph.D. dissertation, Dept. Elect. Eng., Spain, Polytechnic Univ. of Catalonia, Barcelona

[12] Prego-Borges J L 2010 The Lamb Matlab® toolbox first release beta version 0.1 [Online] Available: http://www.mathworks.com/matlabcentral/fileexchange/28367-the-lamb-toolbox

[13] Reibold R and Kažys R 1992 Radiation of a rectangular strip-like focussing transducer. Part 1: harmonic excitation *Ultrasonics* **30** 49–55

[14] Reibold R and Kažys R 1992 Radiation of a rectangular strip-like focussing transducer. Part 2: transient excitation *Ultrasonics* **30** 56–59

[15] San Emeterio J L and Ullate L G 1992 Diffraction impulse response of rectangular transducers *J. Acoust. Soc. Am.* **92** 651–62

[16] Benny G and Hayward G 2000 Beam profile measurements and simulations for ultrasonic transducers operating in air *J. Acoust. Soc. Am.* **107** 2089–100

[17] Pavlakovic B N, and Rose J L 1994 The influence of finite-size sources in acousto-ultrasonics *NASA Contractor Report 195374*