Visualization of Lamb Wave Propagation in Uncured CFRP and Curved Surfaces Using Air-Coupled Ultrasound.

M. D. Fariñas, H. Calás and T. E. Gómez Álvarez-Arenas
UMEDIA research group.
Spanish Scientific Research Council, CSIC
Madrid, Spain, tgomez@ia.cetef.csic.es

***Abstract*— Propagation of Lamb waves, generated and detected using air-coupled piezoelectric transducers (0.1-1.0 MHz), is visualized. Hence phase and group velocities are obtained. The technique is first tested on plates (aluminum and carbon fiber reinforced polymers –CFRP- plates). Then it has been applied to un-cured CFRPs plates and curved surfaces: steel pipes and vessels and to the curved section of CFRP beams. Two different experimental set-ups are proposed: 1) use of monolithic transducers and mechanical scans along the direction of propagation, 2) use of a phased array linear transducer and an electronic scan along the direction of propagation.**

Keywords: uncured CFRP, Lamb waves, air-coupled ultrasound.

I. Introduction.

Lamb waves have largely been used for the ultrasonic study and inspection of plate materials. For fluid loaded plates, the use of the Cremer's or coincidence rule is one of the means to generate and sense this kind of wave. Air-coupled ultrasounds have been used many times in the past along with this coincidence rule. It was used to study paper [1], to develop tomographic techniques, [2], [3] to characterize materials using a through transmission technique [4] to steel plates using narrowband composite transducers [5] and as an imaging technique [6]. In cylindrical shells, Lamb wave-like propagation has also been studied: axial and circumferential Lamb waves. Circumferential C-Lamb waves were first studied under water coupling conditions, [7], [8] but, recently, non-contact techniques are being used [9]. More recently, a NDT technique based on the visualization of laser generated Lamb waves has been proposed. [10].

In this paper, a visualization technique is proposed to simultaneously determine group and phase velocities. Two similar procedures have been tested. The first make use of two single element transducers while the second uses a linear array and one single element transducer..

II. Materials.

An aluminum plate (1.7 mm thick) and three CFRP plates (1.1, 2.1 and 7.75 mm thick) have been studied. In all cases we compared measured and calculated phase and group velocities. In addition, two CFRP plates have also been studied before curing (1.1 mm and 7.75 mm thick). Study of uncured CFRP plates is especially important for two main reasons: 1) contact with the plate is completely impossible and, 2) use of Lamb waves can be questioned by the very low value of material rigidity. Finally the technique has been applied to three curved surfaces: 1) Steel pipe, in the axial direction, (inner diameter 30.34 mm, wall thickness 1.5 mm), 2) Pressure steel tank in the circumferential direction (inner diameter 150 mm, wall thickness 4 mm), 3) The curved intersection of two glass fiber reinforced plates (9 mm thick and at 45 degrees) of a beam for civil engineering applications.

III. Visualization of Lamb Wave propagation using air-coupled transducers. Experimental set-up.

A. *Use of two single element transducers and mechanical scan along the propagation direction.*

A schematic representation of the experimental set-up is shown in Fig.1. Total distance of the mechanical scan was 130 mm with a step of 0.5 mm. Three different pairs of transducers (centre frequency at 0.25, 0.65 and 1.0 MHz) have been used [11]. A Panametrics 5078 pulser/receiver has been employed.

As an example of the obtained measurements, Figs. 2.a and 2.b show a waterfall representation of the a-scans measured at 0.25 MHz with two single element transducers in 1.7 mm thick aluminum and 2.1 mm thick CFRP. Differences between phase and group velocities are clearly appreciated. The relatively higher attenuation in the CFRP can also be appreciated.

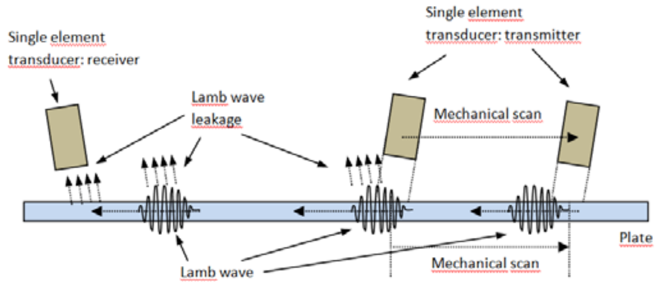

Figure 1. Schematic view of the experimental set-up to visualize Lamb wave propagation in plates using two single element air-coupled transducers and mechanical scan along the propagation direction.

Financial support from the "Ministerio de Economía y Competitividad" through project DPI 2011-22438 is acknowledged.

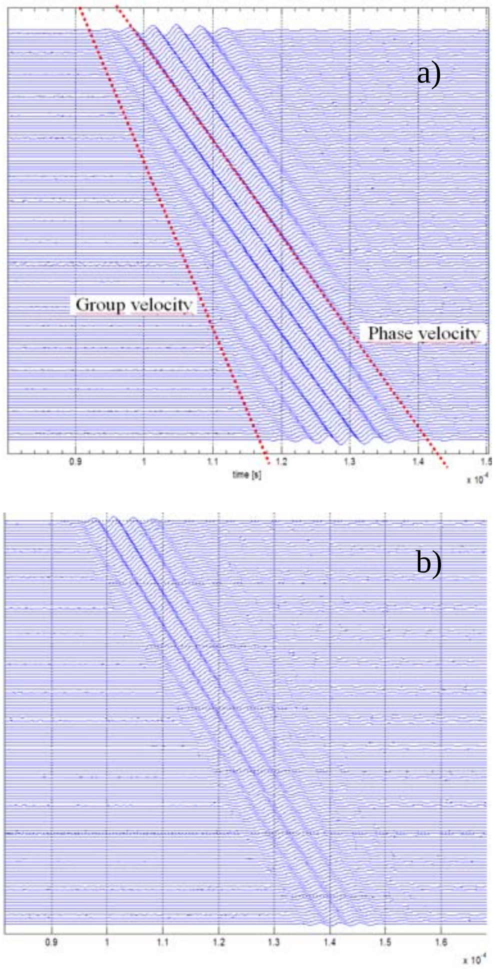

Figure 2. Waterfall representation of the a-scans of the Lamb wave received when the distance between transducers is increased (total scan distance: 130 mm, steps: 0.5 mm and 0.25 MHz. a) Aluminium, b) Cured CFRP.

B. Use of a single element transducer (receiver) and a linear array (transmitter) .

A schematic representation of the experimental set-up is shown in Fig.3. Centre is 0.75 MHz. The array has 32 elements, and the active aperture used is set to contain 5 elements. Aperture was electronically scanned along the array length as shown in Fig. 3. A SITAU equipment developed by DASEL has been used to drive the array and to electronically scan the active aperture. As an example, Fig. 4 shows the measured Lamb wave a-scans in the aluminum plate.

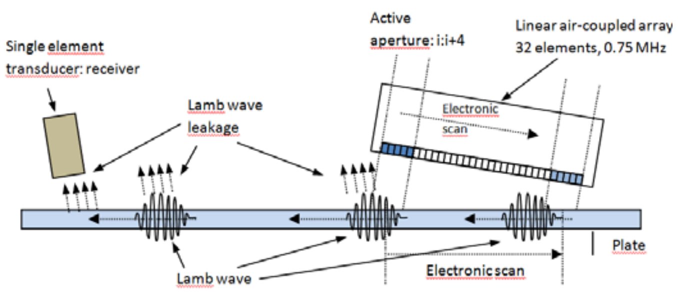

Figure 3. Schematic view of the experimental set-up to using one air-coupled linear array (transmitter) and one single element (receiver).

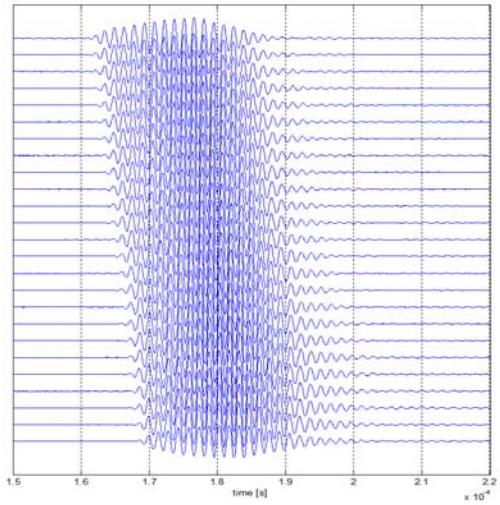

Figure 4. Waterfall representation of the a-scans of the Lamb wave received in the receiver transducer when the distance travelled by the Lamb wave is increased. Aluminum plate and linear array and sigle element transducers.

C. Curved surfaces.

Three different cases were studied. Axial propagation in a steel pipe (inner diameter 30.34 mm, wall thickness 1.5 mm), circumferential Lamb waves in a pressure steel vessel (inner diameter 150 mm, wall thickness 4 mm) and propagation across the curved intersection of two plates of glass fiber reinforced plates (at 45 degrees) of a beam for civil engineering applications. Thickness of these glass fiber reinforced plates was 9 mm and on one side it was loaded with a polyurethane foam. A schematic representation of the experimental set-ups and tested materials is shown in Fig.5. To illustrate the obtained measurements, Fig. 6 shows a waterfall representation of the a-scans measured at 0.25 MHz with two single element transducers in the aluminum pipe in the axial configuration (see Fig. 5.a). Differences between phase and group velocities are clearly appreciated.

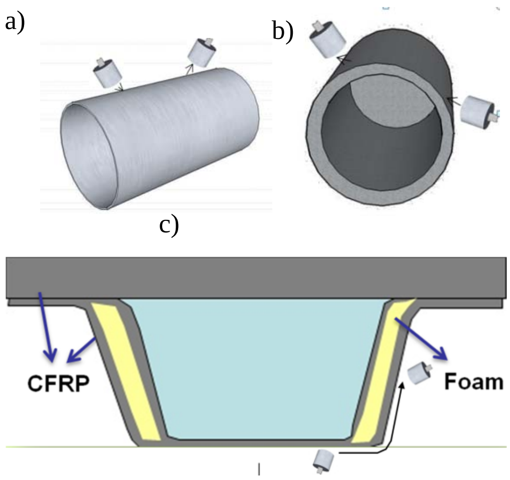

Figure 5. Schematic representation of the experimental set up for the study of axial Lamb wave propagation ina steel pipe, circumferential Lamb wave in a pressure vessel and Lamb wave propagation along in the curved section of a beam.

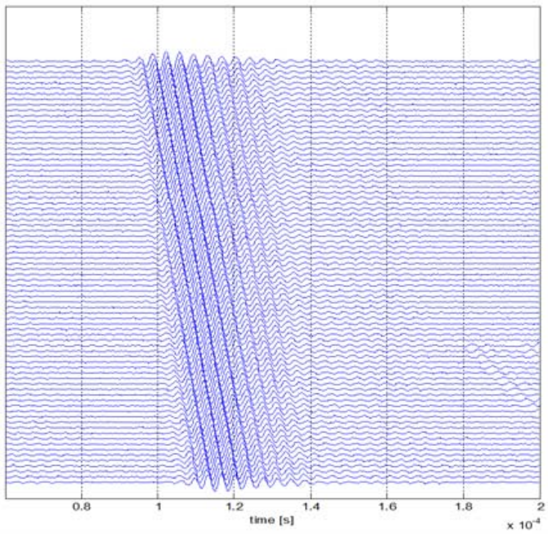

Figure 6. Waterfall representation of the a-scans of the Lamb wave received in the receiver transducer when the distance travelled by the Lamb wave is increased. Steel pipe and 0.25 MHz. Difference between phase and group velocity is clearly appreciated.

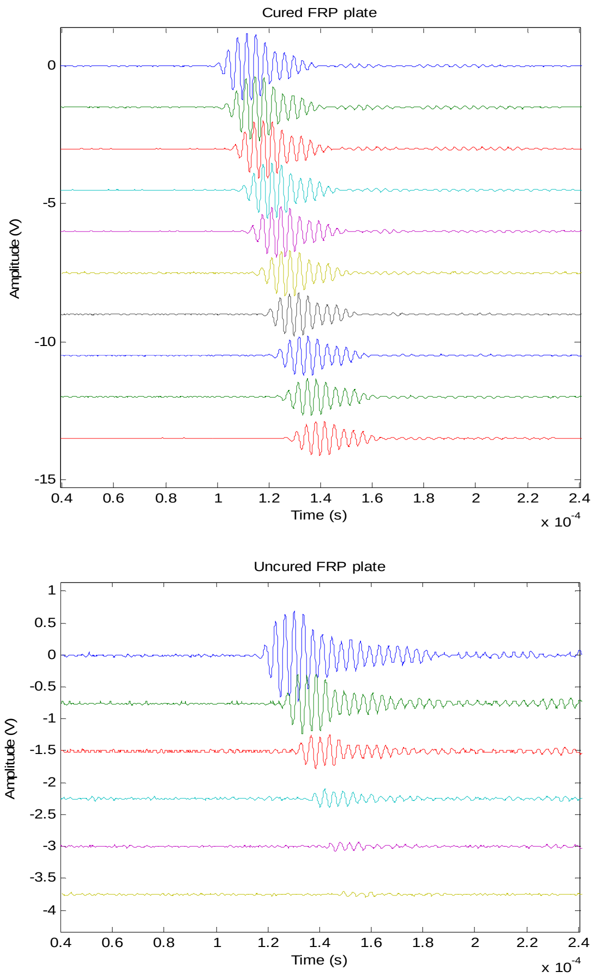

Figure 7. A-scans of the Lamb wave received in the receiver transducer when the distance travelled by the Lamb wave is increased in steps of 5 mm.

IV. Detection of Lamb waves in uncured CFRP.

The major problem in this case is the very large attenuation coefficient. Figure 5 shows the comparison between received signals after different distances travelled in the plate for the cured 2.1 mm thick and the uncured 1.1 mm thick CFRP plates. Estimated attenuation coefficients for the A_0 mode in the cured plate is 150 Np/m at 0.25 MHz, while it is 1000 Np/m for the uncured plate. Similar observation were possible in the 7.75 mm thick uncured plate at 250 kHz. The main restriction of this large attenuation coefficient refers to the distance that the Lamb wave can effectively travel in the plate, which is reduced to a few centimeters.

V. Determination of Phase and Group velocity.

In both experimental set-ups the distance travelled by the Lamb wave is stepwise increased. The incremental distance is small enough so that both phase and group delay can be traced as the distance is increased (see Figs. 2, 3 and 7). Phase delay is determined directly from the variation in the time of arrival of a point with constant phase in the received signal.

To determine group velocity we made use of the Hilbert transform. Group delay is determined from the elapsed time between the peak of the Hilbert transform of successive a-scans. Figure 8 shows the time-displacement of the Hilbert transform measured in the CFRP at 0.65 MHz as the distance between transmitter and receiver is increased.

VI. Experimental Results.

First group and phase velocity of A_0 Lamb wave were measured at: 0.25, 0.65 and 1.00 MHz, then these values are compared with theoretical dispersion relations. This is done for aluminum and cured CFRP plates. Experimental and theoretical values are in good agreement. This can be considered as a validation of the technique. As an example, comparison between experimental and theoretical data for CFRP are shown in Fig. 9. The rest of the obtained experimental measurements are collected in Table I.

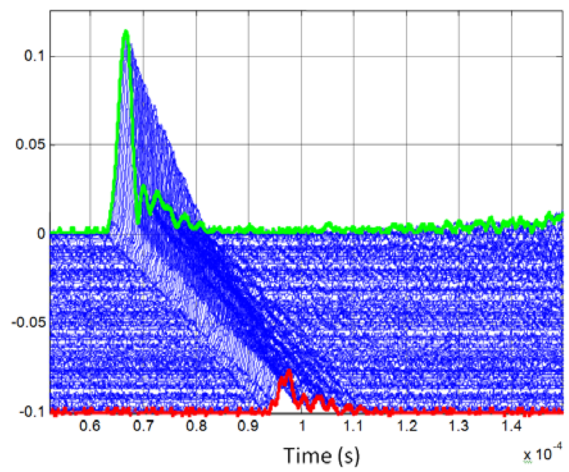

Figure 8. Waterfall representation of the Hilbert transform of the Lamb wave as the distance between transducers is increased. CFRP plate 0.65 MHz.

TABLE I. MEASURED A_0 LAMB WAVE PHASE AND GROUP VELOCITIES.

Material	*0.25 MHz*		*0.65 MHz*		*1.00 MHz*	
	Phase	*Group*	*Phase*	*Group*	*Phase*	*Group*
Aluminum	1560	2540	1790	2910	2275	2980
CFRP (cured)	1390	1600	1560	1678	1790	1323
CFRP (uncured)	--	943	--	1100		
Steel Pipe axial	1790	2694				
Steel vessel (C-lamb)	--	3290	--			

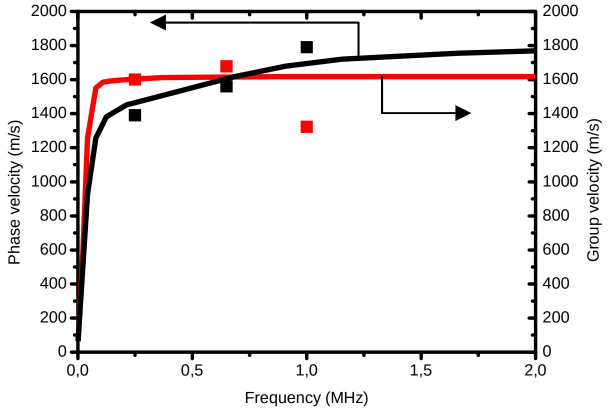

Figure 9. Phase (black) and group (red) A_0 Lamb wave velocities in the 2.1 mm thick CFRP plate. Solid line: theoretical relation dispersions, Dots: experimental data.

VII. CONCLUSIONS.

Air-coupled transducers 0.15-1.0 MHz) have been used to excite and sense pulses of the A_0 mode Lamb wave in several materials (plates and shells). Two methods have been proposed and successfully applied to visualize the propagation of the Lamb wave and hence to get phase and group velocities. In one case two single element transducers are used and one of them is scanned along the Lamb wave direction of propagation. In the other one, one single element transducer and a linear array are used. The linear array is aligned with the Lamb wave direction of propagation. The active aperture is electronically scanned along the array length so that we, effectively, change the distance travelled by the Lamb wave in the material.

Measured and calculated phase and group velocity for aluminum and CFRP plates are in good agreement. In addition, the technique was also applied to uncured CFRP plates and it was possible to measure a A_0 Lamb wave that propagates with a relatively lower velocity, compared with cured CFRP, and with a much higher attenuation coefficient.

The technique has also been applied to measure phase and group velocities in axial propagation in a steel pipe and for circumferential Lamb waves in a steel pressure vessel.

REFERENCES

[1] M. Luukkala, P. Heikkila ,and J. Surakka, “Plate wave resonance - a contacless test method,” *Ultrasonics*, October, pp. 201–208, 1971..

[2] D. A. Hutchins, J. K. Hu, R. P. Young, R. Stoner, D. Jansen, and Q. L. Zhang, “Ultrasonic tomography of metals using non- contact transduction,” *J. Acoust. Soc Am.*, vol. 85, pp. 747-752, 1989.

[3] W. Wright, D. Hutchins, D. Jansen, and D. Schindel, “Air-coupled Lamb wave tomography,” *IEEE Trans. Ultrason., Ferroelect. and Freq. contr.*, vol. 44, no. 1, pp. 53–59, 1997

[4] A. Safaeinili, O. I. Lobkis, and D. E. Chimenti, D. E. “Air-coupled ultrasonic estimation of viscoelastic stiffnesses in plates”. *IEEE Trans. Ultrason., Ferroelect. and Freq.Cont.*, *43*(6), pp. 1171–1180, 1996.

[5] M. Castaings and P. Cawley, “The generation, propagation, and detection of Lamb waves in plates using air-coupled ultrasonic transducers,” *J. Acoust. Soc. Am.*, vol. 100, no. January, pp. 3070–3077, 1996.

[6] S. D. Holland, and D. E. Chimenti, “Air-coupled acoustic imaging with zero-group-velocity Lamb modes,” *Appl. Phy. Lett.*, *83*(13), pp. 2704–2706, 2003.

[7] M. S. Choi, H. C. Kim, and M. S. Yaag, “Propagation characteristics of elastic circumferential waves in nuclear fuel cladding tubes,” *Ultrasonics*, vol. 30, pp. 213-219, 1992.

[8] H. Überall, a. C. Ahyi, P. K. Raju, I. K. Bjørnø, and L. Bjørnø, “Circumferential-wave phase velocities for empty, fluid-immersed spherical metal shells,” *J. Acoust. Soc. Am.*, vol. 112, no. 6, pp. 2713, 2002.

[9] H. Nishino, T. Asano, Y. Taniguchi, K. Yoshida, H. Ogawa, M. Takahashi and Y. Ogura, “Precise Measurement of Pipe Wall Thickness in Noncontact Manner Using a Circumferential Lamb Wave Generated and Detected by a Pair of Air-Coupled Transducers”, *Jpn. J. Appl. Phys.*, vol. 50, pp. 07HC10, 2011.

[10] S. Yashiro, “An NDT technique for composite structures using visualized Lamb-wave propagation,” *Comp. Sci. Technol.*, vol. 67, pp. 3202–3208, 2007

[11] T. E. Gómez Alvarez-Arenas, “Acoustic impedance matching of piezoelectric transducers to the air. *IEEE Trans. Ultrason., Ferroelec., Freq. Contr.*, 51(5), pp 624–633, 2004.

[12] M. Zipparo, C. Oakley, and W. Hackenberger, “Single crystal composites, transducers, and arrays,” *in 1999 IEEE Ultrasonics Symposium*, pp. 965-968, 1999.

[13] T. Ritter, X. Geng, and K. K. Shung, P. D. Lopath, S-E. Park, T. R. Shrout, “Single crystal PZN/PT-polymer composites for ultrasound transducer applications,” *IEEE Trans. Ultrason., Ferroelec., Freq. Contr.*, vol. 47(4), pp. 792-800, 2000.

[14] K. Ren, Y. Liu, X. Geng, H. Hofmann, and Q. Zhang, “Single crystal PMN-PT/epoxy 1-3 composite for energy-harvesting application,” *IEEE Trans. Ultrason., Ferroelec., Freq. Contr.*, vol. 53(3), pp. 631–638, 2006.

[15] K.-B. Kim, D. K. Hsu, B. Ahn, Y.-G. Kim, and D. J. Barnard, “Fabrication and comparison of PMN-PT single crystal, PZT and PZT-based 1-3 composite ultrasonic transducers for NDE applications,” *Ultrasonics*, vol. 50(8), pp. 790–797, Aug. 2010.

[16] K. Cheng, H. L. W. Chan, C. L. Choy, Q. Yin, H. Luo, and Z. Yin, “Single crystal PMN-0. 33 PT/epoxy 1-3 composites for ultrasonic transducer applications,” *IEEE Trans. Ultrason., Ferroelec., Freq. Contr.*,50(9), 1177-1183, Jan. 2003.

[17] S. Cochran and P. Marin-Franch, “Ultrabroadband single crystal composite transducers for underwater ultrasound,” in *2005 IEEE Ultrasonics Symposium*, pp. 231-234, 2005,

[18] G. Hayward and A. Gachagan, An evaluation of 1-3 connectivity transducers for air-coupled ultrasonic applications, *J. Acoust. Soc. Am.*, 99(4), pp. 2148-2157, 1996.

[19] H. E. Bass, L. C. Sutherland, A. J. Zuckerwar, D. T. Blackstock, and D. M. Hester, “Atmospheric absorption of sound: Further development,” J. Acoust. Soc. Am., vol. 97, pp. 680‑683, 1995.

[20] M. N. Jackson, "Simulation and control of thickness-mode piezoelectric transducers," University of Strathclyde, U.K. Ph.D. thesis, 1984.