IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 20, 2019, accepted December 24, 2019, date of publication January 17, 2020, date of current version January 27, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2967211

The Suitability of Using 3D PLA Printed Wedges for Ultrasonic Wave Propagation

ANTONIO J. BALVANTÍN[1], ERICK ROJAS-MANCERA[1], VICTOR A. RAMIREZ[1], JOSÉ ÁNGEL DIOSDADO-DE-LA-PEÑA[1,2], PABLO ALBERTO LIMON-LEYVA[3], AND RAFAEL ALFONSO FIGUEROA-DÍAZ[3]
[1]Department of Mechanical Engineering, Universidad de Guanajuato, Salamanca 36885, México
[2]College of Science, Technology, Engineering, and Mathematics, Youngstown State University, Youngstown, OH 44555, USA
[3]Department of Electric and Electronics Engineering, Instituto Tecnológico de Sonora (ITSON), Ciudad Obregón 85130, México

Corresponding author: Antonio J. Balvantín (antonio.balvantin@ugto.mx)

This work was supported by the PROFEXCE 2020 through the University of Guanajuato.

ABSTRACT This work studies the suitability of using 3D printed PLA wedges made through additive manufacturing to propagate Lamb waves in plate structures instead of using rather more expensive commercial wedges. Ultrasonic waves were propagated in test samples printed at different densities to determine the optimal printing features of ultrasonic wedges based on signal attenuation. Results show barely any difference in Lamb wave filtered effect between 3D printed PLA and commercial wedges, which supports its usage as a suitable and cheaper option for Lamb wave propagation.

INDEX TERMS Layered manufacturing, acoustic waves, ultrasonic transducers.

I. INTRODUCTION

Civil, aerospace and mechanical infrastructures are constantly under critical environmental conditions, which might cause damage on structures that could lead to a catastrophic failure. Structure health motoring is a particularly challenging task, and ultrasonic Lamb waves have been proposed as an alternative approach for non-destructive structural assessment of large structures, due to their high sensitivity to discontinuities along their path, scanning capabilities, and long-range propagation for inaccessible areas with low energy loss [1], [2]. However, dispersion and multimode are some of the Lamb wave characteristic phenomena that occur during its propagation, making the signal analysis difficult to interpret.

Some common techniques to attempt mode isolation and avoid multimode phenomena are based on actuator design, for example, a comb-type array or an angled beam device, the latter also known as wedge. Other techniques have been proposed as ways of isolating Lamb wave modes, such as controlled mechanical impact, electromagnetic acoustic transducer (EMAT), magnetostrictive transducer, laser transducer, or center frequency and frequency spectrum transducers, among others [3]. The advantage of being able to select (isolate) a specific mode simplifies the signal processing analysis and its interpretation. Lucite and acrylic are the most common materials for manufacture of ultrasonic wedges and have been used in many research projects to select a specific wave mode [4]–[7]. Other materials such as steel have been used to manufacture wedges in triangular geometries to focus the transducer wave beam on a point on the test specimen [8]. Commercial wedges have also been used in pipelines to monitor slurry properties during radioactive waste transfer [9]. However, most of commercial wedges are configured at a specific angle that makes it difficult to propagate different wave modes; even variable angle beam wedges might not be capable of selecting a specific wave mode due to their manufacturing and geometric properties. Also, acrylic and Lucite wedges are quite expensive, with an average price around $300 USD per wedge.

Currently, additive manufacturing (AM) has gained great interest in multiple industrial sectors, and many universities and educational institutions have been making efforts to democratize knowledge in this area. The most common way to manufacture three dimensional objects by laying consecutive layers of material in AM is using 3D printers [10], [11]. The interest in using AM in new areas is growing, since it has some advantages over traditional manufacturing processes, including the creation of complex geometries, low cost, less timewasting in manufacture, a variety of materials,

The associate editor coordinating the review of this manuscript and approving it for publication was Jiansong Liu.

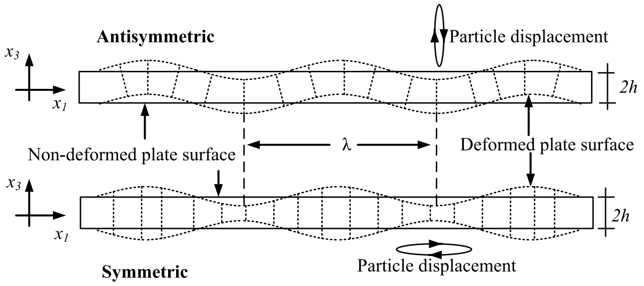


FIGURE 1. Schematic of plate deformation and particle displacement in antisymmetric and symmetric guided waves modes.

low requirements for installation and the initial investment, among others [12], [13]. Despite these advantages, AM developments have some deficiencies with regard to manufacturing effectiveness, its accuracy and the functionality of finished parts [13].

This paper proposes the development of an experimental study for the characterization of the propagation of ultrasonic waves through 3D printed pieces. The main objective is to be able to select a specific Lamb wave mode using 3D printed wedges. The effects of different parameters, such as printing density and direction, on the propagation characteristics of ultrasonic signals are also studied. Finally, the use of 3D printed wedges for mode selection of ultrasonic Lamb wave signals is also projected.

A. LAMB WAVES

The basic theory of wave propagation in systems with free boundaries has been well known for a long time. Lamb [14], described the mathematical solution for the wave propagation in traction-free homogenous and isotropic plates. Two types of wave modes can be generated in a free plate, called symmetric and antisymmetric wave modes. Figure 1 shows the plate deformation generated by Lamb wave propagation.

The equations to estimate the phase velocity for a specific frequency-thickness are called Rayleigh-Lamb relations. For symmetric modes, these can be written as:

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

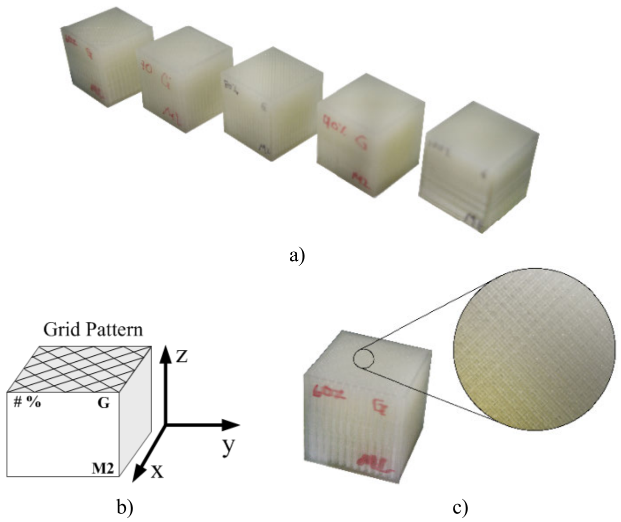
and for antisymmetric modes:

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

Equations (1) and (2) are used to estimate the phase velocity from a specific frequency-thickness product where:

$$p^2 = \left(\frac{\omega}{C_L}\right)^2 - k^2; \quad q^2 = \left(\frac{\omega}{C_T}\right)^2 - k^2, \qquad (3)$$

and k represents wave number of Lamb waves, ω is the angular frequency, h is the plate thickness and C_L and C_T are the longitudinal and shear velocities, respectively.



a)

b)

c)

FIGURE 2. PLA printed cubes: a) with different printing densities and b) printing pattern and printer global coordinate system orientation. c) Zoom-in of grid pattern.

With (1) and (2) only the phase velocity dispersive curves are obtained. The group velocity dispersive curves are obtained from the phase velocity dispersive curves, as follows:

$$C_g = C_p^2 \left[C_p - (fd)\frac{dC_p}{d(fd)} \right]^{-1}. \qquad (4)$$

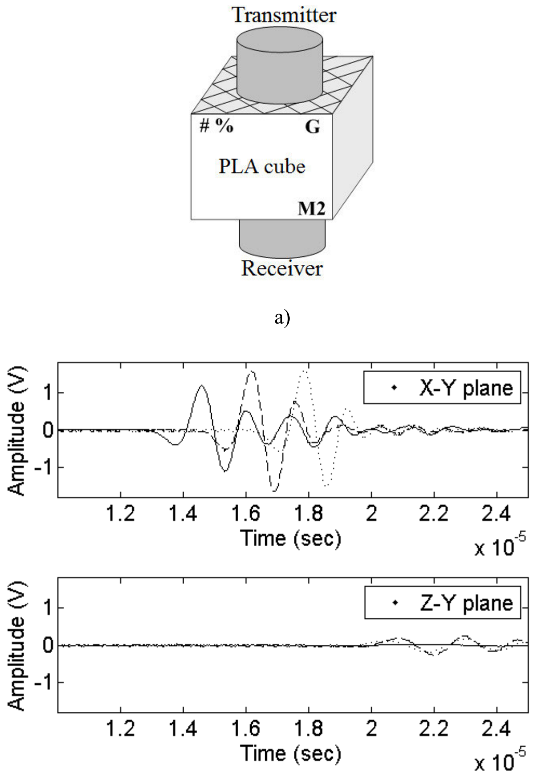
where fd denotes frequency times thickness, C_p is phase velocity and C_g group velocity.

II. EXPERIMENTATION

The design of the PLA wedges began by taking into account the parameters: printing orientation, printing density, and infill geometry of pieces, since these considerations affect the mechanical properties of the 3D printed pieces [13].

Five PLA 3D printed cubes with 60, 70, 80, 90 and 100% of printing density (Figure 2a), were analyzed to determine signal attenuation along the testing samples. The printing orientation (Figure 2b), and printing density of printed cubes were characterized by propagating bulk wave throughout the cubes to determine in which printing density and orientation the wave propagates with a higher amplitude.

The cubes were printed on an Anycubic®i3 Mega 3D printer with a working volume of 210 × 210 × 205 mm^3. The mechanical arrangement of the printer is Cartesian-XZ-Head, which means that the bed moves on the Y axis, and the head on the XZ axis. A commercial TriGorilla®mainboard is used to control the 3D printer, with a resolution of 0.05 mm to 0.3 mm. The maximum temperature of the printhead nozzle is around 275°C, with capacity to print pieces with densities from 0% (no infill material) to 100% (solid piece). The printing material was a polylactic acid (PLA) filament of 1.75 mm in diameter.



a)

b)

FIGURE 3. a) Schematic of experimental measurements in continuous transmission configuration; b) signals generated with 60% (solid line), 80% (dashed line) and 100% (dotted line) of printing density, and propagated through the printing direction on XY plane (above) and transversally to the printing direction on ZY plane (below).

A. PRELIMINARY RESULTS

Experimental signals propagated in 3D printed cubes, using a continuous transmission configuration (see Figure 3a), are shown in Figure 3b. As can be seen, signals that propagated transversally to the printing direction (ZY plane), have a constant delay of 2 μs per 20% less printing density for the range between 60% and 100%. Additionally, the amplitude of the propagated signals is very low when compared with signals propagated throughout the printing direction (XY plane).

This induced delay in the time of flight (TOF) and also the attenuation of the propagated signals hinders the parameter identification and defect detection processes. On this basis, it is possible to establish that propagation of ultrasonic signals, transversal throughout the printing direction, is not recommended.

In contrast, when the ultrasonic signals propagate throughout the printing direction (XY plane), signals with significant good amplitude are generated with up to seven times greater than those propagated transversally to the printing direction. In addition, only slight artifacts appear next to the original pulse. Finally, it can be observed that the amplitude of the artifacts increases as the printing density decrease.

Figure 4 shows the attenuation coefficient (α) from signals obtained throughout the printing direction of cubes. Signal amplitude from an 80% printed density cube was taken as a reference to determine the attenuation coefficient, since it was the highest amplitude measured from the printed cubes. Also, at least five tests were performed to obtain the attenuation coefficient, with a confidence interval of 95%, defined with an error bar per printing density data, as shown in Figure 4.

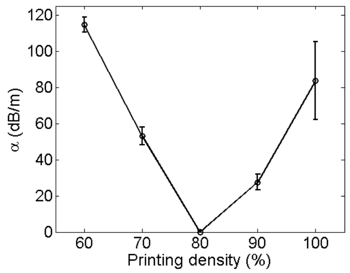


FIGURE 4. Attenuation coefficient (α) between cubes at different printing densities.

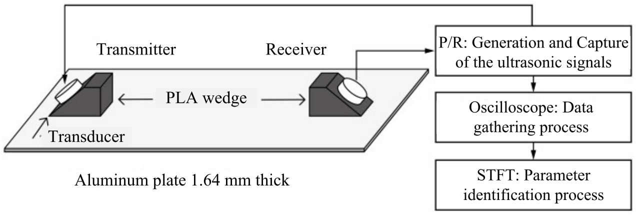


FIGURE 5. Experimental set up scheme for 3D printed wedges.

B. WEDGE TESTING

To test the performance of the proposed PLA wedges, two piezoelectric transducers with a central frequency of 1 MHz were used. The nominal size of the transducers is 17.8 mm (0.7 inch) in diameter and 16 mm (0.63 inch) in height. The transducers were attached to the PLA wedges as shown in Figure 5. Glycerin was used as coupling agent between the sensor, PLA wedges and aluminum sample plate. The same configuration was implemented for commercial variable angle beam wedges. The ultrasonic testing was performed using a pulse/receiver (5077PR Olympus®) to excite the contact transducer. The digitalization of information measured with the transducer was carried out with an oscilloscope (Keysight®Technologies DSO1004A) and a CPU. Two sets of PLA wedges were tested, to generate S0 and A0 modes, with angles of 22° and 48°, respectively; these were then reoriented in order to obtain the appropriate printing direction in function of the angle θ, as shown in Figure 6. Only S0 mode was obtained with a commercial variable angle beam wedge, due to its manufacturing characteristics, which do not allow filtering of A0 mode only.

Figure 7 shows the printed PLA wedges with the transducers on them. In accordance with Snell's Law, 48° and 22° angles were set on PLA wedges in order to generate A0 and S0 Lamb wave modes, respectively.

III. EXPERIMENTAL RESULTS

Figures 8a and 8b show Short Time Fourier Transform (STFT) from signals obtained with PLA printed wedge

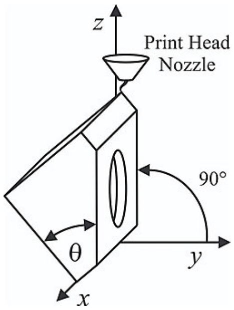
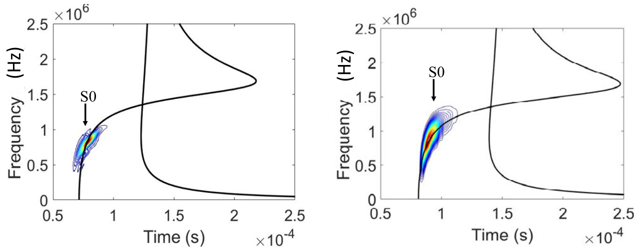


FIGURE 6. **Wedge print orientation (where θ is the incident angle).**

a) b)

FIGURE 7. **PLA printed wedges (48° and 22°) printed to obtain A0 and S0 mode respectively. a) Frontal and b) top view of PLA wedges.**



a) b)

FIGURE 8. **STFT obtained from signals measured with a) PLA wedge and b) variable angle beam wedge.**

and acrylic variable angle beam wedge, S0 Lamb wave mode is identified in both graphics by overlapping theoretical dispersion curves. As can be seen, S0 mode can be obtained with the PLA printed wedge, in a similar way to when it is compared with the results from the commercial acrylic variable angle beam wedge. The distance between the wedges in both tests was 320 mm; however, the time of flight in both STFT presented in Figure 8 is different, since the longitudinal velocity in PLA is around 1.7966 mm/μs, and the longitudinal velocity in variable angle beam wedge is 2.720 mm/μs. Also, the dimensions of both PLA and variable angle beam wedges were different. Nonetheless, these differences in both longitudinal velocities and geometrical characteristics between 3D printed and commercial wedges, does not represent any problem for ultrasonic Lamb waves propagation in practical implementations.

Figure 9 shows STFT from signal obtained with PLA printed wedge at 48°, where a TOF of 125 μs was identified. At this angle, only A0 Lamb wave mode is generated. In contrast, commercial variable angle wedges were not capable of generating A0 mode, given that the estimated angle cannot be set on this wedge.

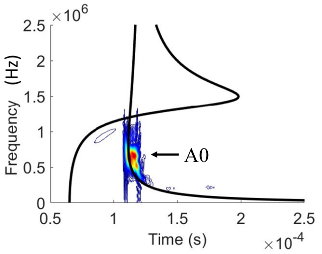


FIGURE 9. **STFT obtained from signals measured with PLA wedge (A0 mode).**

IV. CONCLUSION

This work has analyzed the propagation of ultrasonic waves in PLA, firstly, by printing PLA cubes at different densities (60% to 100%), then by propagating ultrasonic waves in the printing direction (perpendicular to XY plane) and transversally to the printing direction in cubes (parallel to XY plane). Results in printed cubes show that, compared with other densities, maximum amplitude is obtained on signals at 80% of printing density. A constant time delay was observed (around 2 μs) in signals propagating transversally to the printing direction. Also, wave propagation in the printing direction has a better performance, resulting in signals around seven times greater than those propagated transversally to the printing direction. The printer XY plane was considered to print the orientation of PLA wedges. Two sets of PLA wedges were printed at 48° and 22°, which generate A0 and S0 Lamb wave modes, respectively, in an aluminum sample plate. After being analyzed with STFT and theoretical dispersion curves for aluminum plate, the analysis validated the generation of A0 and S0 Lamb wave modes using PLA wedges. The main advantages of using 3D printed ultrasonic wedges are the low cost, if compared with commercial methods, since a single commercial acrylic or Lucite wedge has an average price of $300 USD, while the cost of a pair of 3D printed PLA wedges (with 100% of printing density) is around $5 USD. Additionally, almost any desired incident angle for wedges can be printed to filter specific wave modes.

REFERENCES

[1] Z. Su and L. Ye, *Identification of Damage Using Lamb Waves: From Fundamentals to Applications*. Berlin, Germany: Springer, 2009.
[2] J. D. N. Cheeke, *Fundamentals and Applications of Ultrasonic Waves*,1st ed. Montreal, QC, Canada: CRC Press, 2002.
[3] J. Rose, *Ultrasonic Waves in Solid Media*, Cambridge, U.K.: Cambridge Univ. Press, 1999.
[4] S. Zhang, H. Jeong, S. Cho, and X. Li, "Nonlinear Rayleigh wave sound fields generated by a wedge transducer," in *Proc. AIP Conf. Publishing*, 2016, vol. 1706, no. 1, Art. no. 060010.
[5] J. L. Blackshire, "Enhanced damage characterization using wavefield imaging methods," in *Proc. 43rd Annu. Rev. Progr. Quant. Nondestruct. Eval.*, 2017, vol. 1806, no. 1, Art. no. 090008.
[6] M. H. Park, I. S. Kim, and Y. K. Yoon, "Ultrasonic inspection of long steel pipes using Lamb waves," *NDT E Int.*, vol. 29, no. 1, pp. 13–20, 1996.
[7] K. Shivaraj, K. Balasubramaniam, C. V. Krishnamurthy, and R. Wadhwan, "Ultrasonic circumferential guided wave for pitting-type corrosion imaging at inaccessible pipe-support locations," *J. Pressure Vessel Technol.*, vol. 130, no. 2, 2008, Art. no. 021502.

[8] G. Rus, S.-C. Wooh, and R. Gallego, "Design of ultrasonic wedge transducer," *Ultrasonics*, vol. 43, no. 5, pp. 391–395, Mar. 2005.

[9] M. S. Greenwood and J. A. Bamberger, "Ultrasonic sensor to measure the density of a liquid or slurry during pipeline transport," *Ultrasonics*, vol. 40, nos. 1–8, pp. 413–417, May 2002.

[10] Y. Huang, M. C. Leu, J. Mazumder, and A. Donmez, "Additive manufacturing: Current state, future potential, gaps and needs, and recommendations," *J. Manuf. Sci. Eng.*, vol. 137, no. 1, 2015, Art. no. 014001.

[11] C. Schelly, G. Anzalone, B. Wijnen, and J. M. Pearce, "Open-source 3-D printing technologies for education: Bringing additive manufacturing to the classroom," *J. Vis. Lang. Comput.*, vol. 28, pp. 226–237, Jun. 2015.

[12] C. B. Williams and C. C. Seepersad, "Design for additive manufacturing curriculum: A problem-and project-based approach," in *Proc. Annu. Int. Solid Freeform Fabr.*, 2012, pp. 81–92.

[13] A. Saldaña, A. D. J. Balvantin, J. A. Diosdado, E. Rojas, and N. Saldaña, "The insertion of low-cost additive manufacturing into engineering teaching: A case in central Mexico," *Int. J. Mater. Product Technol.*, vol. 59, no. 3, pp. 270–287, 2019.

[14] H. Lamb, "On waves in an elastic plate," *Proc. Roy. Soc. London A, Containing Papers Math. Phys. Character*, vol. 93, no. 648, pp. 114–128, Mar. 1917.

ANTONIO J. BALVANTÍN received the B.Sc. degree in mechatronic engineering from the Technological Institute of Saltillo, in 2007, and the M.Sc. and Ph.D. degrees in robotics and advanced manufacturing from the Center for Research and Advanced Studies of the National Polytechnic Institute, México, in 2009 and 2014, respectively. His research interests include quantitative nondestructive evaluation (QNDE) of materials, advanced methods of QNDE using ultrasound, mechanical design, instrumentation, mechanics of interfaces, and development of automatic and robotic systems for nondestructive quality control. He is currently an Associate Professor with the Mechanical Engineering Department, University of Guanajuato, México.

ERICK ROJAS-MANCERA received the B.Sc. degree in computer science engineering and the master's degree in industrial engineering from the Technological Institute of Celaya, in 2008 and 2011, respectively, and the Ph.D. degree in robotics and advanced manufacturing from the Center for Research and Advanced Studies of the National Polytechnic Institute, México, in 2017. He is currently an Associate Professor with the Mechanical Engineering Department, University of Guanajuato, México. His research interests include quantitative nondestructive evaluation (QNDE) of materials, advanced methods of QNDE using ultrasound, and ultrasonic sensor network in plates and cylindrical structures.

VICTOR A. RAMIREZ received the B.Sc. and M.Sc. degrees in mechanical engineering majoring in mechanical design from the University of Guanajuato, in 2007 and 2010, respectively, and the Ph.D. degree in composite materials from The University of Manchester, U.K., in 2015. He was a Postdoctoral Researcher with The University of Manchester, U.K., in 2017. He became an Associate Professor at the University of Guanajuato, in 2018, where he has developed his research expertise in structural analysis and composite materials.

JOSÉ ÁNGEL DIOSDADO-DE-LA-PEÑA is currently a Professor with the Department of Mechanical Engineering, University of Guanajuato, México. He is currently a Visiting Lecturer with Youngstown State University. He has published multiple research articles in conferences and journals related to computer-aided engineering, experimental testing, structural design, and manufacturing processes.

PABLO ALBERTO LIMON-LEYVA is currently a Professor with the Department of Electrical and Electronic, Technological Institute of Sonora, México. He has published multiple research articles in international conferences and journals in several areas, including computer-aided engineering, experimental testing, structural design, and manufacturing processes.

RAFAEL ALFONSO FIGUEROA-DÍAZ received the M.Sc. degree in mechatronics, in 2007, and the Ph.D. degree in mechanical engineering from the National Center for Research and Technological Development, Cuernavaca, México, in 2012. He is currently a Professor with the Department of Electrical and Electronic, Technological Institute of Sonora, México. His current research interests are modal balancing in rotating systems and fault diagnosis using vibration.

• • •