Anisotropic Behavior of Ultrasonic Waves in 3D Printed Materials

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ABSTRACT
This study quantifies the anisotropic behavior of ultrasonic wave transmission for materials printed with three different 3D printers. As 3D printed materials become more prevalent in manufactured products, fully characterizing the physical properties of these materials become more important. This paper examines the longitudinal velocity of sound and acoustic impedance in two directions: orthogonal and parallel to the printed layers. Each of the 3D printed materials displayed slightly different transmission results. For PMMA like samples printed on a SLA printer waves travelled more quickly in the orthogonal direction than the parallel direction. For samples printed on an industrial FDM printer using ABS the opposite was true: the parallel direction was faster than the orthogonal. For samples printed on an entry level FDM printer with PLA there was no consistent pattern, instead there was a tight clustering of ultrasonic velocity in the parallel direction but substantial variation in the orthogonal direction. Overall the variation between the orthogonal and parallel directions was found to be less than 2% in all cases.

KEYWORDS
3D Printing; Additive Manufacturing; Ultrasonic Waves; Anisotropic Material Properties; ABS; PLA

INTRODUCTION
In recent years 3D printing has fundamentally changed the ways that parts are manufactured. Gone are the days when 3D printing was only used for prototyping. From dental implants[1] to aircraft components,[2] 3D printed parts are now being used in a wide range of permanent applications. With this shift towards permanent usage, understanding the material properties of 3D printed parts has become more important than ever. Previous studies have reported on properties like tensile strength and young's modulus.[3–11] To date, however, we are unaware of any studies on the manner in which 3D printed materials transmit ultrasonic waves.

3D printing refers to a collection of additive manufacturing techniques where material is joined in a variety of layer by layer approaches. The desired part is created using Computer Aided Design (CAD) software and then converted to a series of thin layers by the 3D printing software. Perhaps the most common type of 3D printing technology is fused deposition modeling (FDM). FDM printers operate by rapidly extruding a heated polymer filament into the desired layer geometry.[12] The printers typically achieve this by incorporating a nozzle mounted to an X-Y stage. This nozzle moves across a build platform, extruding the filament in thin layers at the desired locations. A Z-stage, either mounted to the nozzle or to the build platform, then moves fractions of millimeters to enable the deposition of material at the next layer. Recently stereolithography (SLA) based printers, which traditionally were much more expensive than FDM printers, have become more affordable and can be found in university makerspaces. SLA, in contrast to FDM, operates by using a laser to selectively cure liquid polymer precursors.[19] Material is still deposited in a layer by layer approach, but due the challenges of accurately moving the focal plane of the laser, the work piece itself is typically repositioned using a Z-stage between layers. There are dozens of other technologies for 3D printing, including direct metal laser sintering, selective laser sintering, and selective laser melting. [12] In this study we report the ultrasonic properties of materials printed using an entry level FDM printer (Ultimaker 2®), an industrial FDM (Stratasys uPrint SE®), and an entry level SLA (Formlabs Form2®). These printers were chosen because they provided a range of material types and were local to the University of San Diego, where this research took place.

Ultrasonic waves have proven to be a powerful and non-invasive method for a wide range of sensing applications including pregnancy screening, proximity sensors, and crack detection.[13] One of the unique features of many 3D printed materials, due to their layer by layer fabrication, is their mechanical anisotropic behavior.[14] Due to the individual layer stacking the properties are variable depending upon the direction that specimens are tested. This happens because of environmental conditions present while cooling, and is inherent to the 3D printing process. We hypothesized, and confirmed in this study, that this anisotropy can have an effect on the way in which ultrasonic waves are transmitted through 3D printed materials.

Ultrasonic waves are sound waves above 20 kHz – the ultra- prefix refers to the fact that waves at these frequencies are above the limit of human hearing.[15] While the mathematical models for ultrasonic waves are quite complex, the fundamental concept is relatively straightforward: when a propagating wave encounters a discontinuity, such as a fetal tissue surrounded by fluid in the womb, reflections are generated that can be measured by an ultrasonic sensor. These waves, like all sound waves, propagate through solids, liquids, and gasses. The mechanism of this propagation is through molecular collisions – hence these waves travel considerably more quickly through solids than through air. When there are no molecules to transmit these vibrations, such as in the vacuum of outer space, there is no sound.

By carefully generating, measuring, and modeling the way these waves move through materials a huge range of technologies has been enabled.[16] Within engineering one of the most common applications for ultrasonics is known as ultrasonic nondestructive evaluation.[15, 17] By measuring the velocity and attenuation of ultrasonic waves it is possible to determine a great deal of information about an unknown specimen, including geometry (including hidden cracks), elastic modulus, or density. This testing technique has been used for decades across a wide range of industries.[13] For example, ultrasonics provides a way to check for hidden defects in composite materials for aerospace applications as well as structural health monitoring for large concrete structures in civil applications.[18, 19] Ultrasonic information can be collected in two ways: either using two transducers – one to create the signal and one to receive it - or a single transducer that serves both functions.

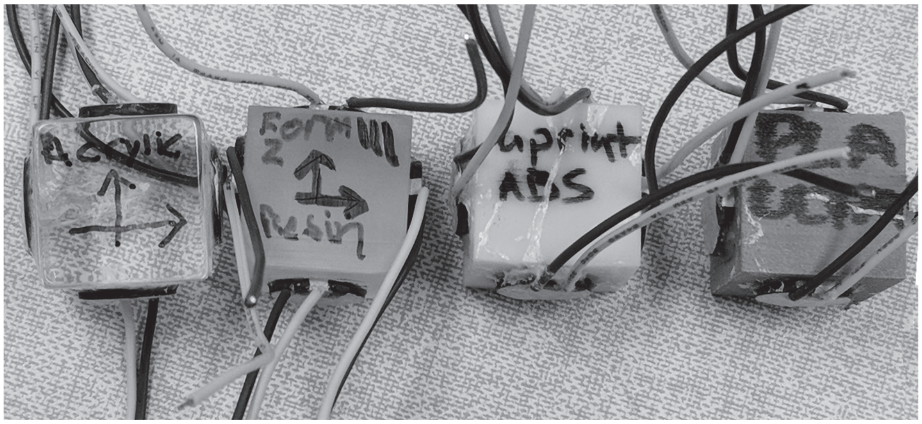
In this study we focus on measuring the properties of longitudinal ultrasonic waves, where molecular motion is parallel to the direction of wave travel, as this type of wave is commonly found in engineering applications. This is the ultrasonic velocity that is used in applications such as ultrasonic distance measurements and flaw detection. Longitudinal ultrasonic wave transmission through a material is typically reported as either the velocity of sound v or the acoustic impedance $Z = \rho v$, where ρ is density.[15] In this paper we report both values and comment on the differences found between the 3D printed materials.

MATERIALS AND METHODS

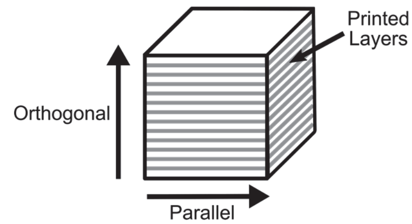
For this study we characterize the material properties for samples printed using three different 3D printers. In this section we describe the sample manufacturing process, how we collected and processed our data, and the statistical approach we took to analyzing our results. These printers were selected primarily due to their availability on our campus, but cover a varied range of possible 3D printing approaches. All printers were configured and calibrated as per manufacturer specifications. As a test specimen we chose to print a 25.4 mm (1 inch) solid cube with a small locating feature on one corner to identify the print orientation. This size was selected primarily as it was the smallest specimen with enough surface to mount our ultrasonic transducers. We printed four copies of each part on each 3D printer for a total of 12 samples. Each sample was then measured in two directions for a total of 24 measurements.

Test part manufacturing

We manufactured parts in three ways: polylactic acid (PLA) printed with an Ultimaker 2, acrylonitrile butadiene styrene (ABS) printed with a Stratasys uPrint, and "clear resin" - similar to poly(methyl methacrylate) (PMMA) - printed with the Form 2 (**Figure 1**). The first printer, the uPrint Stratasys SE, is an industrial fused deposition modeling (FDM) 3D printer. Our model includes a temperature controlled build volume and is capable of printing both ABS filament and a dissolvable support material. We printed parts using a layer height of 100 μm and 100% fill density. (The user is not able to set the extrusion or build volume temperatures for this printer, they are proprietary to the manufacturer.) The second printer in this study, the Ultimaker 2, is an entry level FDM 3D printer. We elected to use a polylactic acid (PLA) filament and printed our part using the standard settings in our makerspace: 268 °C nozzle temperature, 60 °C bed temperature, a layer height of 100 μm, nozzle diameter of 0.6 mm. The only non-standard setting used was a fill density of 100%. The final printer in this study, the Form2, is a stereolithographic (SLA) 3D printer that uses proprietary UV curing resins. We used the "clear resin", similar to PMMA, for our material and selected a layer height of 50 μm. For all printers we chose to print directly on the build platform whenever possible to eliminate the need for support materials that would later need to be removed.



(A)



(B)

Figure 1. (A) The four types of samples, with the ultrasonic transducers installed, tested in this study. From left to right Acrylic (control), Form 2 Clear Resin, uPrint ABS, and Ultimaker PLA. Coordinate systems indicate wave travel directions parallel or orthogonal to the printed layers, and were drawn on the cubes after printing. **(B)** The convention used in this study to define the orthogonal and parallel directions of wave travel. The grey lines indicate the 3D printed layers of the sample. When waves travel parallel to the layers they move along the path of a printed layer. When waves travel orthogonally they move through multiple layers.

Test setup and data collection

We measured the ultrasonic properties of our test samples using a "pitch and catch" configuration with two ultrasonic transducers, (**Figure 2)**. Transducer pairs were installed to measure the ultrasonic properties in two directions – parallel to and orthogonal to the printed layers, (**Figure 1)**. We hypothesized the anisotropic nature of 3D printed parts would lead to variations in ultrasonic velocities.

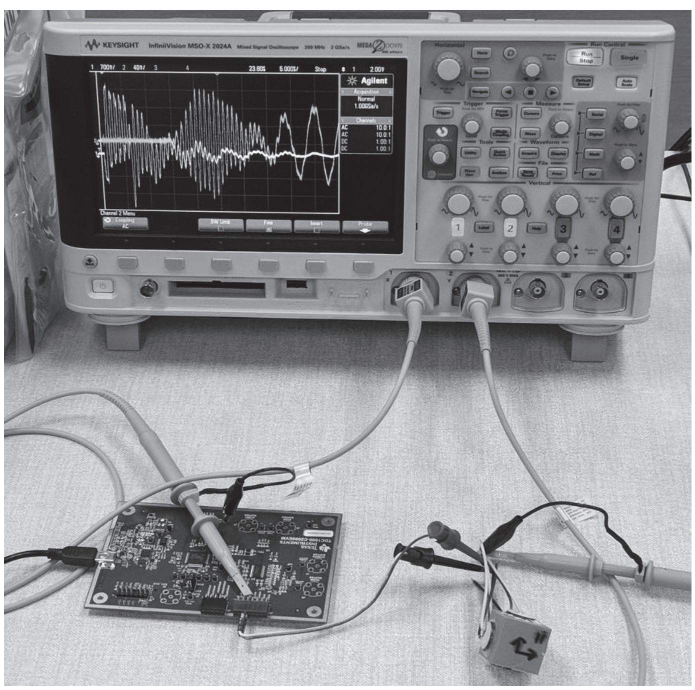


Figure 2. The test setup used in this study. The PCB in the foreground is the Texas Instruments development board we used to generate the 1 MHz ultrasonic pulses, it is connected to the "pitch transducer". The "catch" transducer is connected directly to the oscilloscope which we used to both visualize the signals and store the data. Note that the block shows 4 sensors installed – pitch and catch transducers for both orthogonal and parallel directions.

We selected a 1 MHz Ultrasonic transducer (Steminc® SMD10T2R111) as it is commonly used in engineering applications, including automotive and medical markets. One important note: frequency selection for ultrasonic transducers is highly application dependent. In general, higher frequency waves offer higher spatial resolution, but the signal attenuates more quickly. The 1 MHz wave we selected offers a resolution on distance measurements of approximately ±1 mm. For liquids and solids transducers that produce waves in the MHz range are practical, for transmission through air excitations in the kHz range are preferred. [20]

Following manufacturer recommendations, we cleaned the surfaces of the cubes and then lightly sanded them with 400 grit sandpaper to improve transducer adhesion.[20] We then applied Bob Smith Industries Insta-flex glue™ to the transducers, activated with Bob Smith Industries activator, and pressed them into the center of the cube face. After holding the sensor in place for 60 seconds, we removed the pressure and applied glue around the edges of the transducers to ensure maximum adherence to the block surface.

We used a Texas Instruments TDC-1000 C2000EVM development board to generate the 1 MHz ultrasonic pulse input signal. After some initial testing with one, five, and seven excitation pulses, we settled on a five pulse configuration for our data collection as it provided the optimal balance between signal and noise. We recorded data from both transducers using an InfiniVision ® MSO-X 2024A oscilloscope. We started by setting the sampling frequency to 2 Gsa/s, we then adjusted the settings for each signal to capture as much of the waveform as possible without clipping the data.

Signal processing

The ultrasonic transducer data were processed using MATLAB®. The raw signals were smoothed using a moving average filter. After some experimentation we concluded 100 data points (0.2 μs) was sufficient to remove the noise in the data without substantially reducing the magnitudes of the peaks. We also removed the DC bias in the signal. We used data taken from acrylic blocks, with known ultrasonic properties, to calibrate our system. Acrylic blocks were chosen as a control because they cast blocks lacked the layered properties of the other samples. This property meant the time of flight was similar in any direction through the block for our control, allowing us to find a good detection threshold. We found that a threshold of 25% of the magnitude of the first peak in the received signal correlated with the expected time of flight for an ultrasonic wave through acrylic. We opted to normalize each data set to the magnitude of this first peak, rather than a common voltage threshold, as the material properties for each block resulted in substantially different signal amplitudes. We used this 25% threshold to compute ultrasonic times of flight times for all of the blocks we tested. (**Figure 3** in results shows an example of this threshold and signal.) We then calculated an ultrasonic velocity by dividing the width of the block by the ultrasonic time of flight.

Statistical analysis

As with any material characterization study, it is critical to consider the statistical power of the study. Not enough data and your conclusions are meaningless – too much and you have wasted time and resources. In this case we found that a small sample size (N=4) was sufficient to discern the relevant behavior at each of our measurement conditions. We used a standard single factor analysis of variance (ANOVA)[21] to demonstrate the differences we observed between the three types of printed blocks were statistically meaningful. Within each sample group, we used a paired t-test to compare the parallel and orthogonal velocities for each sample.[21] We selected a paired t-test as our data points were coupled – each block had both an orthogonal and parallel velocity. Using this approach we discovered statistically meaningful conclusions about the differences (or lack thereof) in velocity between the parallel and orthogonal directions.

RESULTS AND DISCUSSION

For each of the three printers we tested the ultrasonic properties of four test specimens. Properties were measured in two directions for each specimen: parallel and orthogonal to the printed layers. An example of the data from a specimen printed with the Form 2 is shown in **Figure 3**, note that this figure shows the post-processed data. The top panel shows the excitation signal. The five pulse ultrasonic excitation can be seen clearly between 0 and 5 μs, the remaining signal shows a typical ultrasonic transducer ring down. The lower panel shows the received signal (solid) and the threshold for computing time of flight (dashed). As discussed in the methods section, we established a threshold for computing time of flight at 25% of the magnitude of the first peak in the received signal.

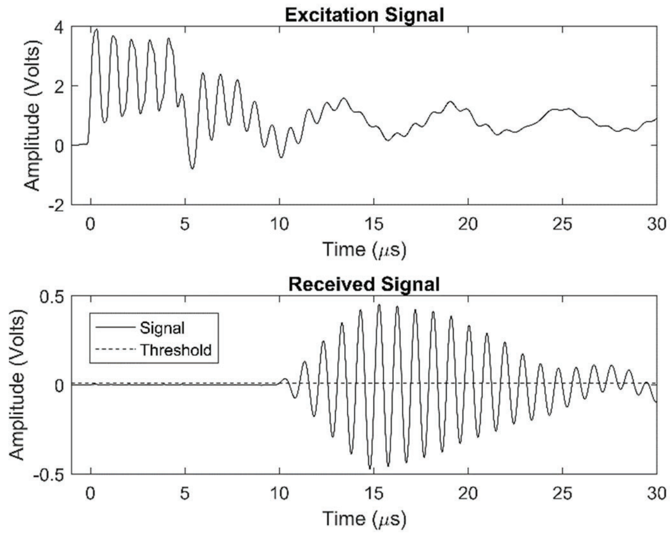


Figure 3. A representative example of the pitch and catch ultrasonic signals collected for this study. Data shown were collected from a Form 2 block in the parallel direction.

The results for the ultrasonic velocities for the twelve specimens are shown in **Figure 4** and summarized in Table 1. Each subplot of **Figure 4** shows the data collected for all of the specimens from a particular type of 3D printer.

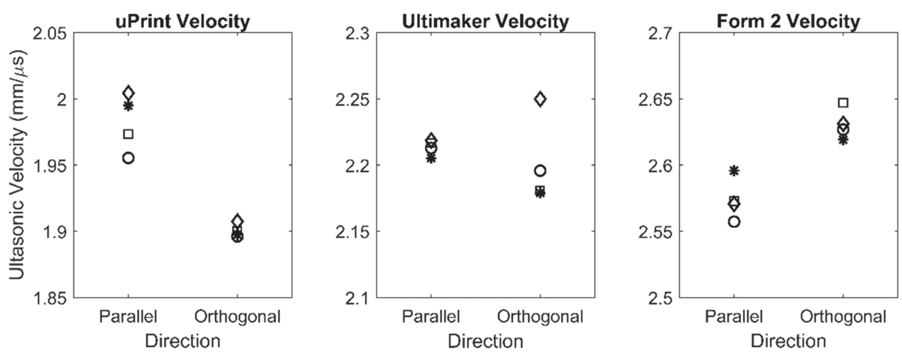


Figure 4. Ultrasonic velocities in the parallel and orthogonal directions for each of the 3D Printers examined in this study. Within each subplot the four samples tested are represented by a unique character (diamond, star, square, or circle).

3D Printed Material	Density g/cm³	Travel Direction Relative to Layers	Longitudinal Velocity of Sound (υ) mm / μs	Acoustic Impedance Z = ϱ υ 10^6 kg / m²s	Deviation Relative to Parallel %	Standard Material Velocity mm / μs
uPrint – ABS	0.97	Parallel	1.70	1.65	-1.8%	2.25
		Orthogonal	1.67	1.62		
Ultimaker - PLA	1.19	Parallel	2.20*	2.62*	n/a*	2.22
		Orthogonal	2.18*	2.59*		
Form2 – Clear Resin	1.14	Parallel	2.58	2.94	2.0%	2.75
		Orthogonal	2.63	3.00		
* We found no statistical difference between these values						

Table 1. Density, Velocity of Sound, and Acoustic Impedance for the samples tested as a part of this work. Reference values are provided for the speed of sound in standard (non 3D printed) materials.[22-23]

Within each subplot a unique marker is used to represent each specimen. This is most cleanly seen in the parallel direction for the uPrint (left most panel) where the velocities are spread out amongst each of the four samples that were tested. In the orthogonal direction, however, these four data points are collapsed on each other. For each specimen we collected a single measurement, represented by the single point on the plot. (During the validation phase of this study we collected multiple measurements for several specimens and found them to be identical. We therefore concluded a single measurement to be sufficient for the full data set.) We computed a one-way analysis of variance (ANOVA) on the time of flight data between the different types of 3D printers and found the differences between each material in our testing to be statistically different ($F=550$, $p=0$). This came as no surprise as each of these printers used a different material. For reference we have included the velocity of ABS, PLA, and PMMA manufactured using traditional means.[22,23] The Ultimaker and Form 2 specimens have ultrasonic speeds similar to those of standard materials, while the ABS printed on the uPrint is substantially lower than the "traditional" stock material.

Within each sample type we computed a paired t-test to determine if the differences between ultrasonic velocities for the two directions (orthogonal and parallel) were statistically meaningful. Both the uPrint ($t= -9.155$, $p= 0.003$) and Form 2 ($t = 4.935$, $p= 0.016$) showed statistical differences as the ultrasonic velocities were quite repeatable. For the Ultimaker, however, there was no quantifiable difference between the two directions as there was wider variations in the velocity between the samples ($t=-0.836$, $p=0.464$). Using the density and longitudinal velocity for ultrasonic waves we calculated an acoustic impedance. These values are shown in **Table 1**.

Interestingly there is a lack of clear trends between the three printers. Coming into the study we hypothesized that ultrasonic waves traveling orthogonal to the print direction would be slightly slower than those waves traveling parallel to the printed layers. We speculated that when traveling parallel to the printed layers, the layers would act as wave guides resulting in higher longitudinal velocities of the ultrasonic waves. While we observed this trend for parts created with the uPrint, the opposite was true for the parts created with the Form 2. An unexpected result was the tight clustering of velocities for a particular direction in the uPrint (orthogonal) and Ultimaker (parallel). This lack of consistent behavior suggests that some other property of these printers changes the transmission of ultrasonic waves. One theory for this could be that the bonds between the layers could be harder than the plastic substrate, making the orthogonal permeability less than the parallel direction. This suggests that for each of these printers the manufacturing process is more consistent with respect to a particular direction. In contrast the Form2 showed similar variations between the data points for a given travel direction.

The major outlier in this group is the Ultimaker. It shows a tight grouping of ultrasonic velocities in the parallel direction, but the samples do not reveal a consistent pattern for the orthogonal direction. Sometimes the orthogonal direction is faster than the parallel, sometimes it is slower. This suggests that something about the layer by layer fabrication process is not always repeatable. This tracks with our broader experience with this printer – of the three printers we find our prints fail the most often on the Ultimaker, producing non-uniform blocks, not finishing prints, or layers separating on removal. More broadly speaking, our results confirm that the anisotropic nature of 3D printed materials does have an impact on ultrasonic velocities. An important note here: 3D printed parts are often printed with lower fill densities (20% – 80%) to speed up printing time and reduce the amount of material needed. For ultrasonic applications we do not recommended this approach: it creates air gaps inside of parts that cause unwanted reflections and substantially attenuate signals. We did test some parts with incomplete infill and found that we could not collect reliable data due to this increased scattering. For applications where ultrasonics will be employed with 3D printing we strongly recommend using 100% infill.

CONCLUSIONS

3D printing is an incredibly powerful technology that has fundamentally shifted the way we think about manufacturing. As 3D printed parts move from prototyping to production, designers must consider the unique material properties of parts made using this approach. While the anisotropic behavior of these materials has been well documented, this study is the first to examine this anisotropy in the realm of ultrasonics. While we have shown clear, repeatable differences in ultrasonic velocities, the variations are relatively small (< 2%). For some applications these variations will be irrelevant, for others, such as the project that motivated this study, a well-developed understanding of ultrasonic behavior in 3D printed parts is critical.

This study is just a first step in investigating the ultrasonic properties of 3D printed materials. There is more work to be done to investigate the specific mechanisms that cause these variations. Future studies would benefit from correlating this ultrasonic data with measurements of Young's modulus and fracture strain using an Instron machine. Similarly, sectioned SEM imaging of specimens in the parallel and orthogonal directions might provide insight into the causes of these variations. It is also possible that there are variations between the two parallel directions of the specimens. (Some 3D printers have been known to create parts that show anisotropic behavior in three directions rather than just two.) Future researchers could also investigate other 3D printing methods or examine the impact of varying specific printing parameters, such as layer height or extrusion temperature, within a particular printer. As designers continue to use 3D printers in innovative ways, we hope the research presented here lays a foundation that will serve them well.

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AUTHOR DISCLOSURE STATEMENT
The authors have no competing financial interests.

AUTHOR CONTRIBUTIONS
EA and GH collaboratively conceived of the study, analyzed the data, and wrote the manuscript. EA conducted all experiments.

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PRESS SUMMARY

This study describes the non-uniform behavior of ultrasonic wave transmission for materials printed with three different 3D printers. The ultrasonic velocity of samples was measured in two directions: orthogonal to and parallel to the printed layers. Each of the 3D printed materials displayed unique behavior. Overall the variation between the two directions was found to be less than 2% in all cases, however these variations could be important in sensitive engineering applications. This fundamental materials research will be useful to engineers designing 3D printed parts for use with ultrasonic waves.