Chapter 9
Optically Detecting Wavefronts and Wave Speeds in Water Using Refracto-Vibrometry

Matthew T. Huber, Brent K. Hoffmeister, and Thomas M. Huber

Abstract Refracto-vibrometry is a technique that uses a laser Doppler vibrometer to measure acoustic pressure fields. The vibrometer laser is directed through a medium towards a stationary retroreflective surface. Acoustic waves (density variations) for which the wavefronts pass through the laser, as the beam travels from the vibrometer to the retroreflector and back, cause variations in the integrated optical path length. This results in a time-varying modulation of the laser signal returning to the vibrometer, enabling optical detection of the acoustic wavefronts. In the current experiment, a Polytec PSV-400 scanning laser Doppler vibrometer, sampled at 100 MHz, monitored the waves emitted by a 1 MHz Panametrics V303 ultrasound transducer immersed in a water tank. The time-varying signal detected by the vibrometer at numerous scan points was used to generate videos of the time evolution of acoustic wavefronts; these videos will be presented. Refracto-vibrometry was also used for optical measurements of the time of flight of ultrasonic waves through different materials, including samples of lead and fabricated bone. This enabled determination of wave propagation speeds. The wave speeds obtained with optical detection using refracto-vibrometry were in agreement with measurements using a conventional ultrasonic transducer to detect the wavefronts.

Keywords Acoustics • Vibrometry • Ultrasound • Refracto-vibrometry • Wave propagation

9.1 Introduction

Ultrasound is used in a wide variety of applications ranging from the medical field to structural testing and dynamics. However, one of the challenges associated with the use of ultrasound is that there are limited non-invasive options available for observing traveling wavefronts and visualizing how they react to their surroundings. This means that systems often must be physically altered in order for one to have an understanding of what is going on in them. Refracto-vibrometry, [1–5] which involves using a laser Doppler vibrometer to optically sample the acoustic field, provides an alternative to the conventional ultrasound measurement methods traditionally performed by transducers.

Much of the research performed with ultrasound takes place underwater because water functions as a coupling medium between the transducer and the object being analyzed. This means the amount of signal attenuated by the water is usually not significant. Ultrasonic transducers, for emission and detection of ultrasonic waves in water, are generally constructed using piezo-electric detectors. When acoustic waves strike the detector, an electrical signal is generated. Alternately, for measurements of acoustic regions with a resolution on the order of 1 mm, needle hydrophones are often used. To characterize sound fields with hydrophones, it is necessary to raster the position of the hydrophone to multiple locations and observe the acoustic field at each point.

Refracto-vibrometry provides an alternative to the conventional methods of characterizing sound fields and analyzing ultrasound signals. The instrument utilized for this technique is a laser Doppler vibrometer [6]. A vibrometer is designed to measure the Doppler shift of a laser after it is reflected from a vibrating surface. However, in the Refracto-vibrometry method used for the current study, the vibrometer is directed at a motionless retroreflective surface and is used to detect the wavefront of the ultrasound pulse [2]. The acoustic waves are fluctuations of the density of the medium, in the current case, water. Because the index of refraction of water is related to its density, acoustical wave density variations also result in a variation of index of refraction. If an acoustic wave passes through the laser from the vibrometer, the index of refraction

M.T. Huber • B.K. Hoffmeister
Department of Physics, Rhodes College, 2000 North Parkway, Memphis, TN 38112, USA

T.M. Huber (✉)
Department of Physics, Gustavus Adolphus College, 800 College Avenue, Saint Peter, MN 56082, USA
e-mail: huber@gac.edu

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variations cause a change in optical path length along the laser's path [5]. The time varying modulation of the laser is detected by the vibrometer, just as it would Doppler shift on the light reflected from a vibrating surface. The vibrometer is thus able to interpret the modulating laser to detect passage of acoustic waves. By repeatedly emitting pulses from a transducer and measuring the time of arrival at acoustic waves at a large number of laser scan points, the vibrometer software can reconstruct an image of a traveling wavefront.

Schlieren photography is a comparable non-invasive technique that can be used for sound field characterization [7]. Schlieren systems, like refracto-vibrometry setups, observe density variations in fluids. In Schlieren systems the density variations create enough of a disturbance in the fluid that sound can be directly imaged using a camera if the fluid is properly illuminated. To produce images of traveling wavefronts, a Schlieren system will sequentially record video frames with successively longer delays between the emission of an ultrasound pulse and a short-duration, very high intensity light flash [8]. While a finely tuned Schlieren system can produce images similar to those produced by a vibrometer, there are several distinct advantages to using a vibrometer. First, vibrometer systems produce easily quantifiable results. The output at each scan point for a vibrometer is a voltage reading that can directly be interpreted in the context of the system being analyzed. With a Schlieren system, quantifying the image produced requires some secondary analysis of variations in intensity recorded in the video pixels. In addition, for refracto-vibrometry the cross-sectional area of the laser beam is the size of the area being observed. This means minute sections can be studied individually, and the beam can be placed wherever a measurement needs to be taken. In Schlieren systems pixels from the video must be picked and chosen for analysis, and this analysis is limited by the resolution of the camera used. Refracto-vibrometry also enables very high time resolution; for example, the system used for the current experiment had a sampling rate of 100 MegaSamples/s.It is clear that refracto-vibrometry is a fundamentally different type of imaging modality compared to conventional techniques. The current study demonstrates two applications of this unique technique: the capability to image traveling wavefronts as they pass through and are reflected from different samples, and the ability to use these detected wavefronts to measure the speed of the sound waves.

9.2 Theory

9.2.1 Refracto-Vibrometry

A vibrometer measures Doppler shift through interferometric techniques. A modulated laser in a Mach-Zehnder interferometer is split into a reference beam that is recombined with a beam that has been reflected from the target [9]. The time variations of the interference pattern are normally due to a Doppler shift of the reflected beam; however, in the case of refracto-vibrometry, the retroreflected target is motionless so the time variations are due to changes in the optical path length between the vibrometer and target. The optical path length, $\varnothing$, is defined as the integral of the index of refraction $n(s)$ along the path the light travels [10]

$$\varnothing = \int_{path} n(s)\, ds. \tag{9.1}$$

When a portion of a wavefront with higher density, thus larger index of refraction, passes through the vibrometer laser, it will increase slightly the optical path length and thus the time the laser takes to travel from the vibrometer to the surface and back. Similarly, a lower density region with lower index of refraction will result in a shorter optical path length and thus shorter light travel time. These alterations in optical path length show up as time variations in the interference between the reference and measurement beam. A noteworthy feature of refracto-vibrometry is that it samples the line integral of density variations along the laser's path. This is different than most conventional ultrasound transducers and needle hydrophones that measure the surface integral of the waves that strike the surface of the detector.

9.2.2 Speed of Sound Measurement

The standard approach to speed of ultrasound measurements involves sending an ultrasound pulse from one transducer to another with no blocking materials. Then, by placing an intervening sample of known thickness, L, in between the transducers, the time-of-flight difference can be used to find the speed of the sound wave through the sample, c_s, given the speed of sound in water, c_w [11]

$$TOF = L\left(\frac{1}{c_s} - \frac{1}{c_w}\right). \tag{9.2}$$

The accuracy of this measurement can be increased by measuring the time-of-arrival for multiple thicknesses and using the slope, m, of the linear plot of time of wave arrival versus thickness to calculate the speed of sound in the sample, c_s, using

$$c_s = \frac{1}{m + \frac{1}{c_w}}. \tag{9.3}$$

In the current experiment, this technique was used to determine the speed of sound through a homogenous solid, lead, and a heterogeneous solid, a fabricated bone-like material. The speed of sound was determined using time of ultrasound pulse arrival optically measured with the vibrometer. This was compared to the speed of sound determined using the established technique for time-of-arrival at the receiving ultrasound transducer. This enables direct comparison between the relatively new measurement technique and a conventional method used for speed of sound determination.

9.3 Experimental Setup

The setup for detection of incident, reflected, and transmitted wavefronts and speed of sound through different samples involved pointing the vibrometer laser into a glass water enclosure housing two ultrasound transducers, the sample, and all of the supporting fixtures. A schematic of this setup can be seen in Fig. 9.1. A 1 MHz Panametrics V303 ultrasound transducer was used to generate acoustic waves. This transducer emitted waves with a near field length of 26.9 mm. The transducer was held in place by a clamp. Cylindrical support rods running alongside the transducer held a tray 23.9 mm above the transducer that had a 37 mm diameter hole. This enabled the sample to be supported by its edges and ensonified by the transducer below. When no sample was present, no reflections of the emitted pulse were observed to reflect from the support structure. In addition, the entire support system was rigid, and was not subject to vibrational modes due to the transducer releasing a pulse.

A second 1 MHz Panametrics V303 ultrasound transducer was used as a receiver of the ultrasound signals. The receiving transducer was oriented facing downward 62.3 mm above the transmitting transducer. This spacing was used to ensure all

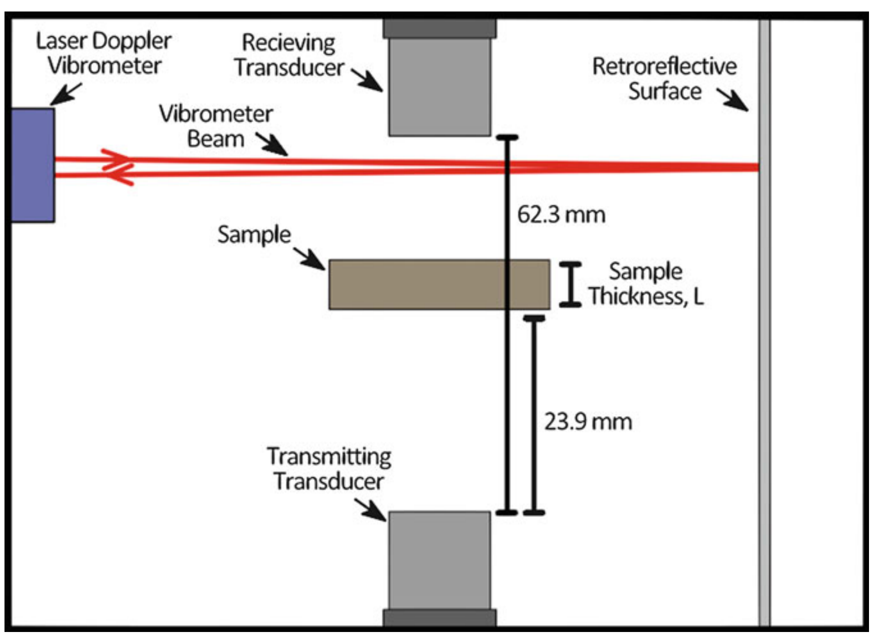

Fig. 9.1 Experimental setup for refracto-vibrometry and transducer wave readings. For wave detection experiments, the vibrometer beam scanned through points around the whole system. For speed of sound measurements, the vibrometer recorded time-of-flight from wave emission at the transducer to wave arrival at a point past the sample

the samples could fit between the transducers without needing to vary the distances. Behind this vertical transducer/sample arrangement a piece of 3 mm thickness aluminum covered in retroreflective tape was placed to reflect the vibrometer laser. To avoid reflections of the laser from the water tank glass, the enclosure was placed at an angle of approximately 15° from being normal to the laser.

Signals for the ultrasound transducers were produced and processed using a Panametrics 5055P pulser [12]. The signal for the emitting transducer was a single, narrow negative voltage pulse. Ultrasound signals that arrived at the receiving transducer were amplified by the pulser to produce an analog output signal. Coincident with the emission of the ultrasound pulse, the pulser output a TTL trigger pulse.

A Polytec PSV-400 scanning laser vibrometer [6] was used for optical detection of the ultrasound wavefronts. The laser was emitted from the vibrometer, passed through the glass face of the tank into the water filled region of the tank, was reflected off a retro-reflective surface, and then returned to the vibrometer along the same path. The mirrors in the vibrometer allowed the laser to be positioned to measure the optical path length variation at many different scan points. The vibrometer velocity decoder was set to a scale that allowed detection of the modulation of the laser signal at frequencies up to 1.5 MHz. For each ultrasound pulse, the TTL trigger from the pulser was used as a trigger for the PSV-400 data acquisition system. The acquisition system digitized, sampling at a rate of 102.4 MSamples/s, a brief pre-trigger interval along with time-domain output of the vibrometer typically for a total of about 80 μs. The vibrometer acquisition system simultaneously can digitize a reference signal; in the current experiment, the reference signal used was the analog output of the pulser that was proportional to the signal measured by the receiving ultrasound transducer. To suppress random noise, the acquisition system averaged between 50 and 1000 individual ultrasound pulses at each laser scan point. By performing these measurements for many separate laser vibrometer scan points, this refracto-vibrometry technique allowed determination of the time-varying acoustic wavefronts.

9.3.1 Optical Detection of 1 MHz Acoustic Wave and Its Reflections

A 1 MHz wave was emitted by the transducer with a 5.9 mm thick lead block placed on the sample tray. The vibrometer scanned through the ultrasound field and measured the signal intensity in the time domain. By compiling all the data points in a two-dimensional grid, the sound field, composed of an emitted wave and all the reflections and transmissions occurring at the sample, could be characterized.

This was repeated without a sample in the tray. By observing the wave traveling from the transmitting transducer to the receiver without interruption, a measurement of the speed of an unattenuated ultrasound wave through water was performed. This was done by finding the distance of wave travel and dividing it by the time of flight from wave emission to reception. By relating the distance of wave travel in an image of the setup to the size of a known object, the actual distance was found. Combining this with the time of flight as measured by the two transducers, the velocity of the wave was determined.

9.3.2 Speed of Sound Measurement Through Lead and Bone

In order to calculate speed of sound through both lead and fabricated bone, different thicknesses of each were used. For speed of sound measurements through lead, four different lead thicknesses were used. For the fabricated bone, five different thicknesses of Sawbones 15 PCF Open Cell bone [13] were cut. The samples were placed underwater in a vacuum chamber for 10 min to remove air pockets from their pores.

Time-of-flight measurements were taken for each of the different thicknesses and for the setup with no sample. Time of flight was determined as being from the time the ultrasound pulse was emitted, to the first major zero-cross time on the received signal; a representative time trace is shown in Fig. 9.2. Frame a of this figure displays the entire signal reading for the vibrometer and transducer. The output signal is seen in the red trace from the transducer several microseconds into the graph. There was a 2.38 μs pre-trigger time period before the pulse emission. The time of flight was measured from the beginning of the sampling period until the zero-cross as marked in frame b of the exploded view of the wave reception portion of the graph. The zero-cross time was chosen as the measurement feature because it is easy to identify and there is a low margin of error in choosing the proper spot.

By combining the previously calculated speed of sound in water with the time-of-flight time for the various thicknesses through Eq. 9.3, it was possible to determine the speed of sound through the different media.

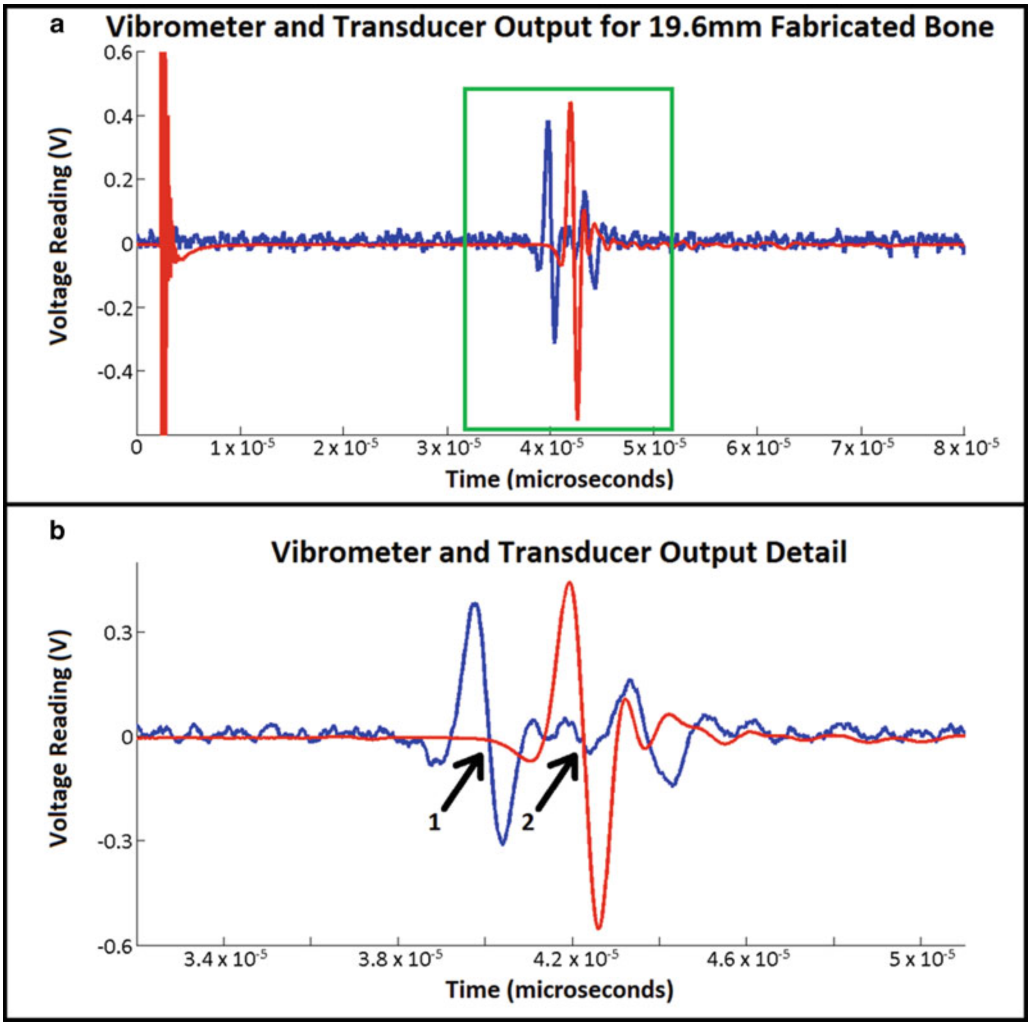

Fig. 9.2 Instrument readings from vibrometer and transducer. The vibrometer beam was placed just below the receiving transducer face in this measurement, and the 19.6 mm fabricated bone was used as the sample. (**a**) The complete time-domain signals from the vibrometer and transducer. The *blue trace* shows the vibrometer output. The vibrometer receives the wave signal before the transducer, seen as the *red trace*, registers the signal. This is expected since the vibrometer beam is positioned slightly in front of the transducer. The large transducer return 2.6 μs into the signal is generated from the electrical noise associated with the transducer emitting an ultrasound pulse. (**b**) Expanded view of boxed section from frame **a**. The zero-cross time-of-flight measurement points are marked. Point 1 is the measured zero-cross time for the vibrometer, and point 2 is the measured zero-cross time for the transducer

9.4 Results

9.4.1 Wavefront Transmission and Reflection

Using the 1 MHz transducer as an ultrasound transmitter and the laser Doppler vibrometer as a refracto-vibrometry wave detector, wavefronts were seen as they were emitted, as they traveled, and after they were transmitted and reflected.

In Fig. 9.3, a wavefront produced by the transducer can be seen at different intervals from when it was emitted. Figure 9.3a shows the wavefront at 12.6 μs after it was emitted. The wavefront is approximately planar, and maintains its shape as it travels vertically up towards the specimen. The speed of the traveling wave was calculated by comparing the distance it moves over a time interval to a known object dimensions. In this case, the transducer was used as the reference object since it had a measured shaft diameter of 15.9 mm. The sound speed in water, as measured this way, was 1460 ± 10 m/s. The accepted value for the speed of sound in water near room temperature [14] is 1483 ± 6 m/s with the uncertainty due to an uncertainty in the temperature of the water in the tank.

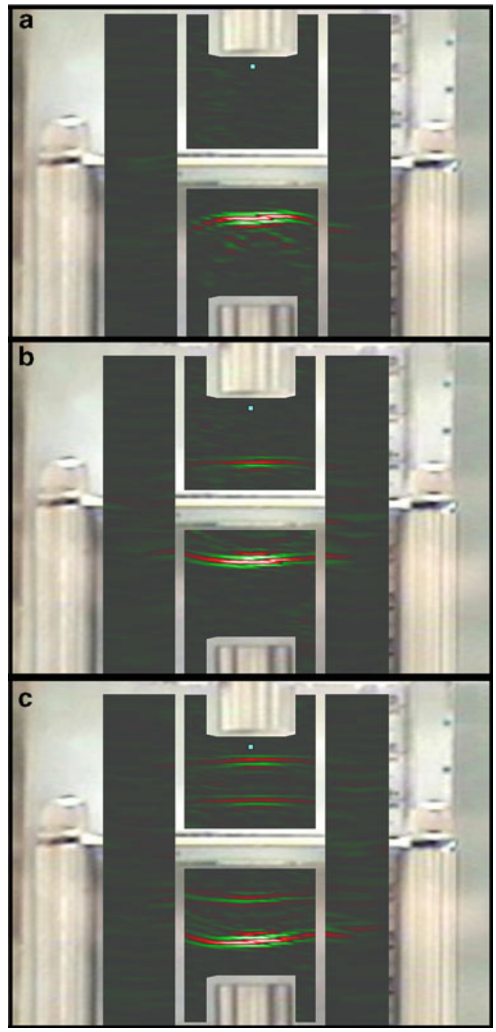

Fig. 9.3 Traveling wavefronts at various points after wave emission. (**a**) Initial wave 12.6 microseconds after release. (**b**) The wave reflected off the sample and the wave transmitted through the sample 24.6 microseconds after transducer ultrasound pulse. (**c**) First reflected and transmitted wave, along with secondary reflections from inside lead 30.6 microseconds after wave emission

When the wavefront came in contact with the 6.35 mm lead plate there was both a transmission and reflection. This transmission and reflection can be seen in Fig. 9.3b, taken 24.6 μs after the emission of the wave. While the transmitted wavefront's speed and shape remains largely unchanged compared to the wavefront incident of the lead plate, the amplitude is somewhat diminished. This is because much of the original wave was deflected downwards by the lead plate. This deflected wave maintains a similar structure to the incoming wave, despite now traveling in the opposite direction back towards its source.

As time progresses further after the wave emission, more reflections can be seen from the lead plate. Figure 9.3c shows the positions of the wavefronts after 30.6 μs. In the time since the last image, the upper and lower waves have continued their progressions in their respective directions. Their amplitudes, speed, and shape remain constant. In addition to these two waves, two new wavefronts are visible at this time. These waves originate from the waves reverberating inside the lead plate.

9.4.2 Speed of Sound Measurement in Lead

Four different thicknesses of lead disks were used, in addition to a measurement with an empty target. This data set is depicted in graphs of Fig. 9.4. The times given are the first zero-crosses of the received signals for either the vibrometer or the ultrasound transducer

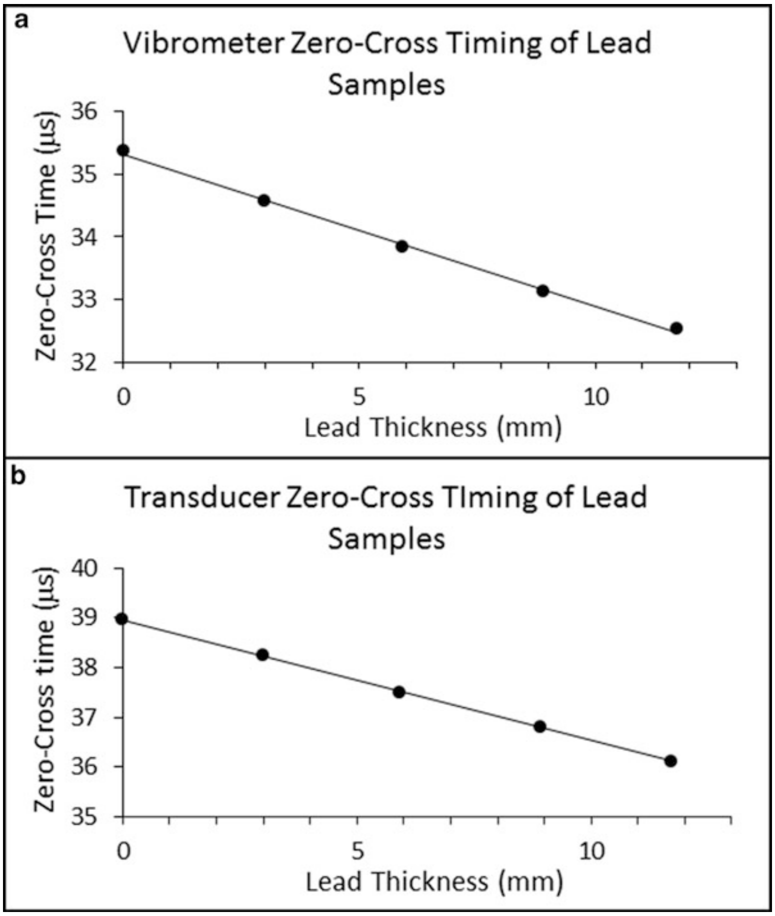

Fig. 9.4 Time of flight versus sample thickness for lead. Note that error bars are present in this data set, but they are small enough that they don't show up relative to the data points. (**a**) Vibrometer measured data. (**b**) Transducer measured data

Using the slope m of the data, and the speed of sound in water previously measured to be $c_W = 1460 \pm 10$ m/s, the speed of longitudinal waves in lead, c_{Pb}, was found using Eq. 9.3. The speed of longitudinal waves c_{Pb} through lead as measured by the vibrometer was 2260 ± 20 m/s. The speed of sound through lead as measured by the ultrasound transducer was 2270 ± 30 m/s. These values are in agreement with each other within the bounds of their uncertainties. These values are slightly larger than accepted values for lead [15] which are 2160 m/s when annealed and 1960 m/s when rolled. It was not known what physical form the lead disks used for this experiment were.

9.4.3 Speed of Sound Measurement in Synthetic Bone

A similar method was used to determine the speed of sound in a synthetic bone material immersed in water. Five different thicknesses of synthetic bone were cut. These thicknesses were used as samples in a speed of sound calculation, along with a trial containing no intervening sample. Both the vibrometer and transducer were placed above the sample so the ultrasound pulse would pass through the sample before being recorded. On the transmitted pulse, the time for the first main zero-cross was recorded for each instrument. Figure 9.5 graphs the resulting time values for each of the fabricated bone thicknesses.

From the slope of the linear fit to this data, the speed of sound was found. For the data taken with the vibrometer the speed of sound through the bone sample is 1507 ± 11 m/s. From the transducer data the speed of sound through the bone samples comes out to be 1497 ± 13 m/s. There have been no published studies discussing the speed of sound in this synthetic bone media. However, the measured speed is roughly consistent with the 1500 m/s speed of waves in cancellous bone material [11].

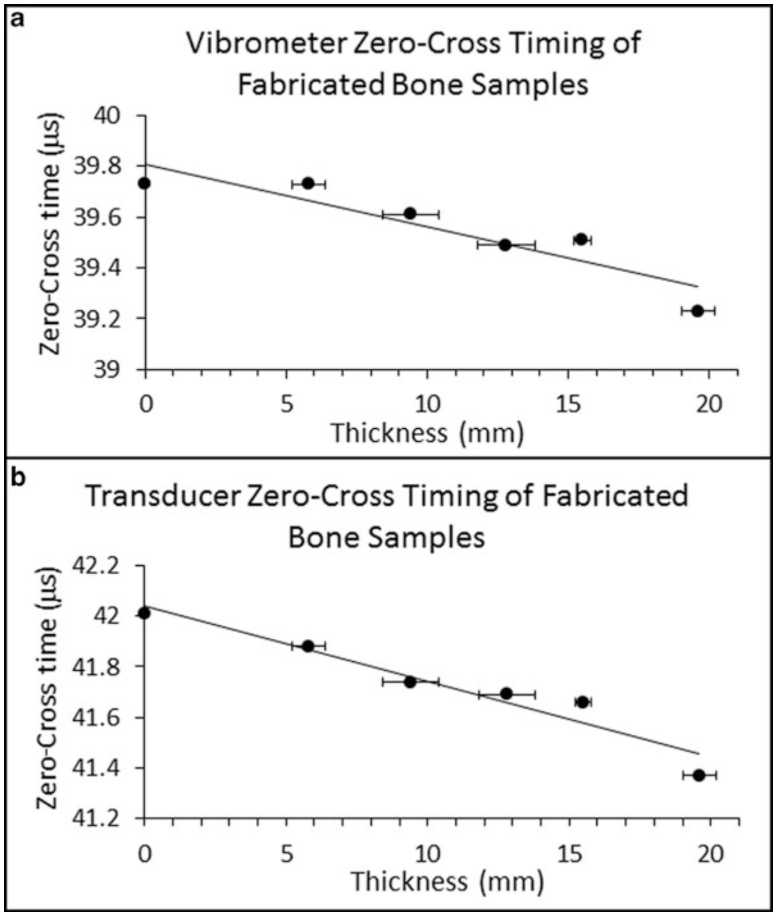

Fig. 9.5 Time of flight versus sample thickness for fabricated bone. (**a**) Vibrometer measured data. (**b**) Transducer measured data

9.5 Conclusions

This study compared a vibrometer used with refracto-vibrometry techniques to conventional transducers. By scanning the vibrometer beam, it was possible to create videos of the transducer transmitting ultrasonic pulses through water. This is valuable because it allows for examination of the ways sound is reflected off and transmitted through various materials. Looking at how ultrasound scatters off a diffuse scattering media like bone is of particular interest as Osteoporosis diagnosis is commonly done by making inferences on bone structure from the signals that pass through the bone.

The refracto-vibrometry technique was shown to be comparable to transducers when it comes to make quantitative measurements of ultrasound waves. Speed of sound calculations through both homogeneous and heterogeneous solids produced results that believable given the sample size and potential for error. These experiments demonstrate that refracto-vibrometry is a viable non-invasive method for characterizing sound fields and obtaining speed of sound measurements through a diverse array of materials.

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