Measurements of ultrasonic phase velocities and attenuation of slow waves in cellular aluminum foams as cancellous bone-mimicking phantoms

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(Received 6 January 2010; revised 14 February 2011; accepted 15 February 2011)

The water-saturated aluminum foams with an open network of interconnected ligaments were investigated by ultrasonic transmission technique for the suitability as cancellous bone-mimicking phantoms. The phase velocities and attenuation of nine samples covering three pores per inch (5, 10, and 20 PPI) and three aluminum volume fractions (5, 8, and 12% AVF) were measured over a frequency range of 0.7–1.3 MHz. The ligament thickness and pore sizes of the phantoms and low-density human cancellous bones are similar. A strong slow wave and a weak fast wave are observed for all samples while the latter is not visible without significant amplification (100×C2).

This study reports the characteristics of slow wave, whose speeds are less than the sound speed of the saturating water and decrease mildly with AVF and PPI with an average 1469 m/s. Seven out of nine samples show positive dispersion and the rest show minor negative dispersion. Attenuation increases with AVF, PPI, and frequency except for the 20 PPI samples, which exhibit non-increasing attenuation level with fluctuations due to scattering. The phase velocities agree with Biot’s porous medium theory. The RMSE is 16.0 m/s at n = 1.5. Below and above this value, the RMSE decreases mildly and rises sharply, respectively.

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PACS number(s): 43.80.Jz, 43.80.Qf, 43.20.Hq [CCC] Pages: 3317–3326

I. INTRODUCTION

Osteoporosis is one of the most common skeletal disorders characterized by reduced bone mass, microstructural deterioration, cortical bone thinning, and cancellous bone perforation leading to fracture risks (Werner, 2005). The prevalence of osteoporotic fractures of the wrists, hips, and spines is a serious public health problem affecting about 200 million people worldwide especially in the aging population (Lin and Lane, 2004). Currently, bone mass is measured by bone mineral density (BMD) using dual energy x-ray absorptiometry (DXA) for bone quality assessment. However, clinical studies indicated that BMD values measured in normal and osteoporotic bones showed considerable overlap (Westmacott, 1995; Legrand et al., 2000; Silverman, 2006); therefore, BMD measurements do not provide sufficient information for accurate diagnosis. Osteoporosis still remains one of the most prevalent undiagnosed diseases in the world today (Nguyen et al., 2004). This is due to the failure to consider bone elasticity and trabecular microstructures by radiation-based methods (Langton et al., 1984; Rossman et al., 1989; Ulrich et al., 1999). These mechanical and structural properties could be potentially assessed by the quantitative ultrasound (QUS) and Langton and Njeh (2004) provided a good review of the method.

Cancellous bone is made up of interconnected network of trabeculae with viscous marrow filling the pores. Because osteoporosis is mostly manifested in the loss of cancellous bone mass and the subsequent disruption of trabecular microstructures (Langton et al., 1984), measurements of ultrasonic attenuation and velocity in cancellous bones have been used to evaluate bone quality (Droin et al., 1998). However, due to high porosity and heterogeneity of human cancellous bones (Gibson, 1985), the underlying mechanisms of interactions between ultrasound and cancellous bones are still not fully exploited or understood (Bossy et al., 2007; Haïat et al., 2008a; Pakula et al., 2008; Wear, 2008a, 2009). Cancellous bone-mimicking phantoms are controllably designed with some desirable characteristic features similar to those of cancellous bones and allow independent study of the influence of these characteristics upon the measurables such as velocity and attenuation. Clarke et al. (1994) and Strelitzki et al. (1997) developed phantoms.

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In this work, commercial open-celled aluminum foams are used as candidates of cancellous bone-mimicking phantoms where the aluminum ligaments simulate the trabeculae. Ultrasonic reports with aluminum foams are so far not many. Ji et al. (1998) did some pioneering studies of the water-saturated aluminum foams and identified both fast and slow waves in transmission-through experiments when the ultrasound beam direction was along the pore elongation; Weaver (1998) studied the modal density of the aluminum foams; Lobkis and Weaver (2001) also studied the modal density, diffusivity, and absorption of the aluminum foams; Lu et al. (1999) studied sound absorption capacity of Alporas aluminum foam. Recently, Le et al. (2010) measured the tortuosity of the aluminum foams using airborne ultrasound as a precursor to investigate the ultrasonic properties of the foams further. The objective of this study is to investigate the frequency-dependent phase velocity, dispersion, and attenuation in water-saturated aluminum foams. The ultrasonic properties of the foams will be discussed and their similarity to those of cancellous bone will be explored. The measured wave speeds will also be compared with the predictions by Biot’s porous medium theory (Biot, 1956a,b).

II. MATERIALS AND METHODS

A. Cellular aluminum foams

The DUOCEL aluminum foams (ERG Materials and Aerospace Corporation, Oakland, CA) are made of 6101 aluminum. The foams are solution heat treated and then artificially aged to a stable condition. The mechanical and structural stability are both substantially improved by the heat treatment. The foam has an open-celled structure with an interconnected network of aluminum ligaments. The foam properties are described by two parameters: the number of cells or pores per inch (PPI) and the aluminum volume fraction (AVF). The matrix of pores and ligaments is completely repeatable. Figures 1(a) and 1(b) show the image and micrograph of a 20 PPI-12% AVF foam sample, respectively. Figure 1(c) shows a schematic diagram of a preferred elongation of the pore structures during the forming process of the aluminum foam samples due to the primary expansion directly from the balance between gravitational and pneumatic forces (Le et al., 2010). The anisotropy of the structural behavior in the elongated direction is around 5%–15% greater than the other two orthogonal directions. We considered three PPIs: 5, 10, and 20, and each PPI has three available AVFs: 5, 8, and 12%. Tables I and II summarize the structural and physical properties of the aluminum foams. All the samples were pre-cut in 50.8 × 50.8 × 12.7 mm³ rectangular prisms. Prior to the experiments, the samples were immersed in distilled water over 24 h to ensure the pores were fully saturated. A few drops of detergent were added

TABLE I. Structural properties of aluminum foams. PPI stands for pores per inch. AVF is the aluminum volume fraction, the ratio of aluminum volume to foam volume. Porosity is given by 1-AVF. The mean cell size (mm) is equal to 25.4/PPI. Al.Th is the aluminum ligament thickness and calculated by mean cell size × AVF. Al.Sp is the ligament separation and is determined by mean cell size × (1-AVF). Le et al. (2010) provides the tortuosity values.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>PPI</th>
<th>AVF (%)</th>
<th>cell size (mm)</th>
<th>Al.Th (mm)</th>
<th>Al.Sp (mm)</th>
<th>Tortuosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5.08</td>
<td>0.26</td>
<td>4.82</td>
<td>1.003 ± 0.001</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>5</td>
<td>0.41</td>
<td>4.67</td>
<td>1.015 ± 0.007</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>6.1</td>
<td>2.54</td>
<td>4.47</td>
<td>1.022 ± 0.002</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>5</td>
<td>0.13</td>
<td>2.41</td>
<td>1.026 ± 0.002</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>0.17</td>
<td>2.33</td>
<td>1.026 ± 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>0.31</td>
<td>2.23</td>
<td>1.029 ± 0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>5</td>
<td>1.27</td>
<td>0.07</td>
<td>1.20</td>
<td>1.030 ± 0.002</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>0.11</td>
<td>1.16</td>
<td>1.032 ± 0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>12</td>
<td>0.16</td>
<td>1.11</td>
<td>1.032 ± 0.003</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
into the water to decrease the surface tension; the samples were occasionally shaken slightly underwater to eliminate air bubbles in the pores.

B. Experimental setup

Figure 2 shows the ultrasonic immersion experimental setup using pulse transmission technique. The experiment used a pair of 12.7-mm-diameter 1.0 MHz unfocused broadband transducers (Panametrics V303-SU, Waltham, MA). The transducers were mounted coaxially on a sample holder with the foam samples placed between the two transducers at near field distance from the transmitter. The ultrasound beam was perpendicular to the pore elongation of the sample as shown in Fig. 1(c) and the whole setup was immersed in distilled water. The speed of sound in distilled water is temperature-dependent (Wear, 2009)

\[
V_{\text{water}} = 1402.9 + 4.835T - 0.047016T^2 \\
+ 0.00012725T^3
\]  

(1)

where \( T \) is the temperature in Celsius. Since the temperature of water was approximately 19.5°C, \( V_{\text{water}} \) was 1480 m/s. The near field distance \( N \) is given by \( N = \frac{D^2}{4\lambda} \), where \( D \) is the diameter of the transducer and \( \lambda \) is the wavelength of ultrasound in water (Cobbold, 2008). In our case, \( N \) is 26.4 mm and the distance between the transducers was set at about twice the focal length (53 mm). Nine regions of interests (ROIs) were scanned for each sample and each ROI was shifted 2 mm from the previous ROI and parallel to the transducer’s surface while maintaining the ultrasound beam well within the sample boundaries. An Olympus 5800 pulse-receiver (Panametrics, Waltham, MA) excited the transmitter; the transmitted signals were received and stored by a LeCroy WaveSuer 422 digital oscilloscope (LeCroy, Chestnut Ridge, NY). The signals were sampled at 2 Gigasamples per second at 8 bit resolution. Each of the digitized

![FIG. 2. (Color online) A schematic diagram of the immersion experimental setup. The distance between transducers was about twice the focal length, \( d \approx 53 \) mm.](image)

![FIG. 3. The ultrasound signals: (a) a water pulse; (b) a sample signal of a 5 PPI-5% AVF foam sample (sample #1) where the box outlines the region where a fast wave exists; (c) the amplitude spectrum of the water pulse; and (d) the amplitude spectrum of the sample signal.](image)
waveform was continuously averaged over 256 times to increase signal-to-noise-ratio (SNR). The signals were later decimated and a small time window of 301 points containing the relevant waveforms was selected for further spectral analysis with zero-padding.

C. Computation of group velocity, phase velocity, and attenuation

For transmission technique, two signals are recorded without and with the sample in the beam path. The former is a reference signal through water (water pulse) and the latter is a sample pulse. The speed of sound of the medium can be determined by the group velocity via the substitution method (Rossman et al., 1989)

\[ V = \frac{h}{-\Delta t + \frac{h}{V_{\text{water}}}} \]  

(2)

where \( \Delta t \) is the delay time between the traveling times of the reference points of the signals, and \( h \) is the sample thickness. In this work, we used the arrival times of the envelope peaks (Le, 1998) to calculate the delay time. When absorption exists, dispersion analysis is useful to examine the traveling speeds of the frequency components via phase velocities (Sachse and Pao, 1977)

\[ c(\omega) = \frac{\omega h}{-\Delta \phi(\omega) + \frac{\omega h}{V_{\text{water}}}} \]  

(3)

where \( \omega \) is the angular frequency and \( \Delta \phi(\omega) \) is the unwrapped phase difference between the reference and sample spectra. However, a least-squares fitted \( \Delta \phi_{\text{lsf}}(\omega) \) is used in Eq. (3) instead and is estimated by the linear least-squares regression fit to the \( \Delta \phi(\omega) \) within the frequency range of interest (Verhoef et al., 1985; Mujagic et al., 2008). Dispersion is characterized by the slope of the linear least-squares regression line fitted to the phase velocity versus frequency data within the same frequency range.

Ultrasonic energy loss due to scattering, absorption, and transmission is quantified by the attenuation coefficient, \( \alpha \) (in dB/cm),

\[ \alpha(\omega) = \frac{20}{\ln 10} \times \log_{10} \left[ \frac{A_{\text{ref}}(\omega)}{A_{\text{sample}}(\omega)} \right] \]  

(4)

where \( A_{\text{ref}}(\omega) \) and \( A_{\text{sample}}(\omega) \) are the spectra of the reference and sample signals. The attenuation was not corrected for the transmission loss caused by the water-foam interfaces. When the attenuation is normalized by the relevant frequency band, we obtain the normalized broadband ultrasound attenuation (nBUA) in dB/MHz/cm.

Since each sample was measured nine times, the average group velocities, phase velocities, and attenuation were calculated and reported with standard deviations.

III. RESULTS

The water pulse and an example of the 5 PPI-5% AVF (sample #1) sample pulse are shown in Figs. 3(a) and 3(b) and their corresponding amplitude spectra in Figs. 3(c) and 3(d), respectively. The sample pulse was attenuated by 6 dB compared to the water pulse. There was no observable distortion on the wave shape and dispersion, if there is any, was extremely small; the scattered ultrasound between pores within the foam sample is evidenced as small variations in the tail of the main pulse. The portion of the signal

![FIG. 4. The region within the box in Fig. 3(b) was amplified 100 times to show the existence of a fast wave.](image)

### TABLE III. Group velocities, dispersion, and nBUA of aluminum foams.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Group Velocity (m/s)</th>
<th>Dispersion (m/s/MHz)</th>
<th>nBUA (dB/MHz/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1473 ± 2.8</td>
<td>5.35 ± 5.56</td>
<td>4.2 ± 0.7</td>
</tr>
<tr>
<td>2</td>
<td>1472 ± 2.4</td>
<td>12.69 ± 3.07</td>
<td>5.5 ± 1.0</td>
</tr>
<tr>
<td>3</td>
<td>1466 ± 4.2</td>
<td>7.69 ± 4.80</td>
<td>6.5 ± 0.7</td>
</tr>
<tr>
<td>4</td>
<td>1472 ± 2.4</td>
<td>-1.52 ± 1.62</td>
<td>3.5 ± 0.6</td>
</tr>
<tr>
<td>5</td>
<td>1463 ± 2.4</td>
<td>1.12 ± 0.95</td>
<td>3.8 ± 1.2</td>
</tr>
<tr>
<td>6</td>
<td>1467 ± 4.4</td>
<td>5.83 ± 1.47</td>
<td>4.1 ± 1.1</td>
</tr>
<tr>
<td>7</td>
<td>1472 ± 2.4</td>
<td>-2.98 ± 1.44</td>
<td>1.5 ± 0.9</td>
</tr>
<tr>
<td>8</td>
<td>1472 ± 2.4</td>
<td>5.34 ± 2.18</td>
<td>1.4 ± 0.6 *</td>
</tr>
<tr>
<td>9</td>
<td>1468 ± 4.2</td>
<td>15.01 ± 2.81</td>
<td>0.8 ± 1.4</td>
</tr>
</tbody>
</table>

\*For the fixed 0.7–1.3 MHz frequency band, the nBUA value is a small negative number (−0.8 ± 0.5), which renders amplification instead of attenuation. We recalculated the nBUA value using a 0.8–1.4 MHz frequency window.
delineated by the box in Fig. 3(b) was amplified 100 times in Fig. 4 to reveal a weak fast wave preceding the strong slow wave (Biot, 1956a,b); Furthermore, the fast wave has a time period of approximately 1.7 $\mu$s compared with 1 $\mu$s of the slow wave, indicating the dominant frequency of fast wave is about 40% lower than the dominant frequency of the slow wave. The same observations apply to the other eight samples. Since the slow waves dominate the wave propagation, the ultrasound properties of the aluminum foams are governed by the slow waves within the frequency range from 0.7 to 1.3 MHz. The group velocities of the slow waves through the nine samples were calculated via Eq. (2) and tabulated in Table III. The propagating speeds of all samples are similar with an average of 1469 m/s and are less than the acoustic wave speed in water (1480 m/s).

To further examine the ultrasonic properties of the foam samples, we performed spectral analysis on the full wave pulse but focused on the frequency range where the slow waves dominated. Figure 5 shows the phase velocity versus frequency curves for all samples for the 0.7–1.3 MHz frequency range. The selection of the frequency range was based on the full-width-half-maximum (FWHM) of the sample amplitude spectra. The reproducibility for phase velocities was 0.13% calculated by dividing the standard deviation with the corresponding mean value (Giraudeau et al., 2003). All phase velocities are lower than the acoustic velocity in water, which is consistent with the group velocity measurements and further confirms the dominance of slow wave propagation through the samples. For the same PPI samples, the phase velocity decreases with increasing AVF. Furthermore, the majority of the samples exhibit positive dispersion (phase velocity increasing with frequency). Table III lists the dispersion values for the phase velocity curves. The 20 PPI-12% AVF sample (#9) has the largest dispersion ($15.01 \pm 2.81$ m/s/MHz). There are two exceptions; the 10 PPI-5% AVF sample (#4) and 20 PPI-5% AVF sample (#7) display minor negative dispersion (phase velocity decreasing with frequency). Their dispersion values are $-1.52 \pm 1.62$ m/s/MHz and $-2.98 \pm 1.44$ m/s/MHz, respectively.

Figure 6 displays the total attenuation versus frequency curves. The attenuation was not corrected for the transmission loss at the foam-water interfaces. The transmission losses at the interfaces were determined experimentally; the values were small, ranging between 0.005 and 0.015 dB/cm and were ignored. The reproducibility for the attenuation was 10.3%. Generally speaking, attenuation increases with PPI; for each PPI, attenuation increases with AVF; for the 5 PPI, the 8% AVF (#2) and 12% AVF (#3) samples have similar attenuation behavior within the frequency range of interest but different nBUA values, which are $5.5 \pm 1.0$ dB/MHz/cm and $6.5 \pm 0.7$ dB/MHz/cm, respectively (Table III). For the 5 PPI and 10 PPI samples, attenuation increases quasi-linearly with increasing frequency. However, the 20 PPI samples display a fairly constant attenuation level with small variations (less than 1.5 dB/cm).

To investigate the influence of foam structure on the acoustic properties, the phase velocity and attenuation at 1.0 MHz for all samples are plotted in Figs. 7(a) and 7(b), respectively. At fixed PPI, phase velocity decreases with increasing AVF, while the attenuation increases with increasing AVF. The behavior becomes less predictable for various PPI at fixed AVF. First, for the 5% AVF samples (#1, #4, and #7), both phase velocities and attenuation showed minor changes with different PPI (less than 1 m/s
and 0.5 dB/cm). Second, for the 8% AVF samples (#2, #5, and #8), the phase velocities of 5 PPI (#2) and 10 PPI (#5) samples are the same (less than 1 m/s difference), whereas 20 PPI sample (#8) has a smaller phase velocity. Among the three 8% AVF samples, the 5 PPI sample (#2) has the largest attenuation and the 10 PPI sample (#5) has the smallest attenuation. Third, for the 12% AVF samples (#3, #6, and #9), the 20 PPI sample (#9) exhibits a slowest phase velocity while suffers the largest attenuation (12.53±0.89 dB/cm). The phase velocities of 5 PPI (#3) and 10 PPI (#6) samples have minor difference. The same is true for their attenuation.

Biot’s theory was used to predict the slow wave velocities in the aluminum foams. The Biot’s equations for the wave speeds propagating in the fluid-filled aluminum foams are given in details in Appendix A. Tables I and II provide the tortuosity and other parameters required for the computation. The root-mean-squared error (RMSE) was used to measure the difference between the predictions and experiments. The RMSE was obtained by first summing the squared errors of all nine samples between the measured wave speed and the predicted value and then taking the square root of the sum. Figure 8 shows a RMSE curve between the predicted and experimental velocities for \( n \) ranging from 1 to 2. The four \( n \)-values published in the literature: 1 (Gibson and Ashby, 1999), 1.23 (Williams, 1992), 1.46 (Hosokawa and

FIG. 6. The total attenuation versus frequency curves: (a) 5 PPI, (b) 10 PPI, and (c) 20 PPI samples. Attenuation was not corrected for transmission loss, which was experimentally determined to be insignificant.

FIG. 7. The influence of PPI and AVF on the (a) phase velocity and (b) attenuation at 1.0 MHz.
Otani, 1998), and 2 (Gibson and Ashby, 1999) are also labeled in the figure.

IV. DISCUSSION

We studied nine aluminum foam samples with different AVFs and PPIs as candidates to mimic cancellous bone structures. These samples have an open-celled structure formed by an interconnected network of aluminum ligaments with a comparatively low AVF ranging from 5% to 12%. The cancellous bone has a plate-like structure at high densities and an open-celled rod-like structure at low densities (Gibson and Ashby, 1999; Hosokawa and Otani, 2005). The networks of the aluminum foams in this study have high resemblance to the low-density human cancellous bone. Moreover, the majority of these foam samples have ligament thickness (Al.Th) and separation (Al.Sp) close to the reported trabecular thickness (Tb.Th = 0.082 – 0.284 mm) and separation (Tb.Sp = 0.454 – 1.307 mm), respectively (Hildebrand et al., 1999; Ulrich et al., 1999). This is valid for the 20 PPI samples (see Table I) and the structural factors or tortuosities of the 20 PPI samples measured in our previous report (Le et al., 2010) are very similar to the measurements of human vertebral cancellous bone (1.04 ± 0.004) using the same air-borne ultrasound approach (Nicholson and Strelitzki, 1999). However, aluminum has larger elastic modulus and density (Table II) than those of trabeculae (Lang, 1970; Williams, 1992; Keavery et al., 1993; Hosokawa and Otani, 1997), which results in an increased acoustic impedance contrast with saturating fluid and enhances the scattering processes among the ligament-water interfaces.

Biot (1956a,b) predicted two compressional waves propagating through fluid-saturated porous materials. They are the fast and slow compressional waves which are associated to the in-phase and out-of-phase motion between the solid and fluid components, respectively. These two types of waves are nondispersive when the frequency satisfies the condition $\omega > > 2\eta / \rho a^2$, where $\eta$ is the dynamic viscosity of water, $\rho_f$ is the density of water, and $a$ is the pore size (Plona and Johnson, 1980; Johnson and Plona, 1982). Reports on the fast and slow waves in porous solids are abundant but similar reports in cancellous bone are not many (Lakes et al., 1983; Hosokawa and Otani, 1997, 1998; Hughes et al., 1999; Nicholson and Strelitzki, 1999; Hoffmeister et al., 2000; Mohamed et al., 2003; Mizuno et al., 2009). Ji et al. (1998) have successfully observed a fast wave and a slow wave with comparable amplitudes when a 1.0 MHz ultrasound pulse was transmitted along the pore elongation of various 40 PPI water-saturated aluminum foams. The pore orientation of the samples was later provided by the ERG Materials and Aerospace Corporation, Oakland, CA. In the study of Ji et al. (1998) they found the experimental velocities and Biot’s predictions had good agreement for $n = 2$. In our experiments, a strong slow wave pulse was observed and the fast wave could only be seen after 100-folded amplification. Given the values of the dynamic viscosity, $\eta$, and density, $\rho_f$ of water listed in Table II, the viscous skin depth $\delta = (2\eta / \rho_f c_0) / \omega$ at 1.0 MHz is 0.18 $\mu$m, much smaller than the smallest pore size (1.11 mm) of our samples. For these pores, considerable amount of the fluid moved out-of-phase with the solid and consequently, the generation of slow wave was greatly encouraged (Johnson et al., 1982). Also at 1.0 MHz, the waves are nondispersive according to the condition stated earlier.

The calculated group velocities of slow waves range between $1463 \pm 2.4$ m/s and $1473 \pm 2.8$ m/s with an average of 1469 m/s and are consistent with the slow wave phase velocities at 1.0 MHz, which range between $1461 \pm 1.2$ m/s and $1473 \pm 0.6$ m/s. The discrepancies between the two velocity measurements are small (less than 0.4% or 6 m/s) because the dispersion of the samples is very minor. These values fall below the acoustic wave speed of water as expected for slow wave characteristics ($V_{\text{slow}} = V_{\text{water}} / \sqrt{\text{tortuosity}}$). Johnson et al., 1982; Plona, 1980) and within the slow wave velocities (1450–1490 m/s) observed in low volume fraction, (VF ≤ 20%) of cancellous bone (Cardoso et al., 2003). Seven of the nine samples (comprising 78% of the samples) exhibit positive dispersion ($\geq 1.12$ m/s/MHz) while the other two samples ($\# 4$ and $\# 7$) display minor negative dispersion. The abnormal dispersion was first observed in cancellous bone by Nicholson et al., 1996). The phenomenon illustrates the co-existence of several possible mechanisms in addition to absorption when the ultrasound beams interact with the foam samples. The possible causes are the scattering effects (Nicholson et al., 1996) including multiple scattering (Haïat et al., 2008b) and the interference between the fast and slow waves (Marutyian et al., 2006; Anderson et al., 2008; Bauer et al., 2008) even though the fast waves in our case have extremely small amplitudes.

According to the product information (ERG Materials and Aerospace Corporation, Oakland CA), the DUOCEL aluminum foam is formed by an array of bubbles with each bubble being a 14-faceted polyhedron. Once solidified, the foam will leave 14 windows in the 14 facets and aluminum struts as the window frame to create an open cell. Each strut shares between three adjacent bubbles to create characteristic triangular cross sections. The VF determines the
cross-sectional shape and actual size of the strut. The two foam parameters, PPI and AVF, play an important role in the ultrasonic propagation through the samples. The works by many investigators such as Hosokawa and Otani (1998) have shown that the fast and slow waves display opposite behavior with VF. Our samples show the velocities of slow waves decrease with increasing VF (or decreasing porosity), which agrees well with the reported slow wave observations with porosity (Plona, 1980; Cardoso et al., 2003; Mohamed et al., 2003; Hosokawa, 2008). As PPI increases, both the cell and pore sizes decrease. The narrowing of the pores might restrict the fluid motion and increase friction of propagation, thus increasing attenuation of the slow wave and reducing the speed. At fixed PPI, as AVF increases, the same narrowing of the pores occurs. The effects of PPI and AVF on attenuation and wave speed are more prominent for 20 PPI where the wavelength is comparable to the pore size.

The attenuation generally increases with AVF at fixed PPI. The attenuation of 5 PPI and 10 PPI samples increases with frequency, whereas the attenuation of the 20 PPI samples with frequency is less obvious and exhibits a non-increasing attenuation level within the main frequency band. The 20 PPI samples have more pores and as a consequence, a more number of scattering interfaces. This enhances the scattering processes among ligaments within the samples, giving rise to the low intensity random signals affecting the coherent signals and coda. At 20 PPI, the cell size (1.27 mm) and pore size (1.1–1.20 mm) are smaller and comparable to the dominant wavelength (≈1.5 mm). More volume averaging due to a broad pulse is expected when ultrasound beam passes through the samples and thus generates a smoother transmitted signal. Both the scattering and volume averaging are perhaps the dominant processes contributing to the non-increasing attenuation behavior of the 20 PPI samples. The average attenuation of the 20 PPI-12% AVF sample at 1.0 MHz was 12.53 dB/cm and was within 10.5–15.0 dB/cm range as reported in the literature (Strelitzki and Evans, 1996; Hosokawa and Otani, 1998; Chaffai et al., 2000; Mujagic et al., 2008).

Biot’s theory has been applied with some success to predict propagating velocities in cancellous bone (Haire and Langton, 1999). According to Gibson and Ashby (1999), the value of exponent parameter $n$ in Eq. (A9) depends on the structural type of the solid frame and direction of force loading. They modeled cancellous bones as low- and high-density equiaxed structures, prismatic-celled structures, and plate structures. By means of mechanical testing, they obtained $n = 1$ for prismatic-celled structure when the load was along the prism axes and for plate-like structure when the stress was parallel to the plates. The exponent could go up to 2 when the increased perforation in the plate model turned the structure into a low-density equiaxed structure, which is open-celled with a network of rods. Higher exponent such as 3 could be obtained when the stresses were either applied across the prism axes or normal to the plates. Our experiment was different from those of Gibson and Ashby (1999) in two fundamental ways. First, the tested material was different. The DUOCEL foam structure is 14-facet polyhedral with triangular cross-section, which might have larger resistance to compression and deformation. Second, the methodology of the experiments was different. We used ultrasound to create mechanical stresses to the structure while Gibson and Ashby (1999) used mechanical bending. By means of curve-fitting to the experimental data, Williams (1992) found $n = 1.23$ with ultrasound beam parallel to the columnar orientation of the bovine trabeculae and $n = 2.35$ for a random structure. Hosokawa and Otani (1998) used bovine cancellous bone (porosity β = 0.82) and found $n = 1.46$ and $n = 2.14$ depending on whether the beam was parallel or perpendicular to the trabecular alignment. The measured wave speeds were compared with Biot’s predictions using a range of $n$-values ranging from 1 to 2 and the RMSE is shown in Fig. 8. The four $n$-values: 1, 1.23, 1.46, and 2 are also labeled in the figure. The $n$-value of 2 provided the worst prediction with a RMSE of 172 m/s or 12%. The predictions by the first three $n$-values conform comparatively well to the experimental results with RMSE of 8.8 m/s ($n = 1$), 10.7 m/s ($n = 1.23$), and 14.8 m/s ($n = 1.46$), respectively. At $n = 1.5$, the RMSE is 16 m/s or 1%. Below this value, the RMSE declines mildly to 0.6% at $n = 1$ and above it, the RMSE increases sharply and amounts up to 12% at $n = 2$. Except for one sample (#1), the wave speeds of all samples were under-predicted by the theory. The main reasons for the discrepancies could be due to the more complex porous structure of the foams than the Biot’s porous materials and the presence of the scattering processes which were not accounted for by the theory.

V. CONCLUSIONS

The ultrasound properties of water-saturated aluminum foams were studied experimentally. The ligament thickness and pore size of the foam samples are very similar to those of human cancellous bones. The ligament network has close similarity to the low-density cancellous bone with open-celled rod-like structures. Two waves, one fast and one slow, were observed but the fast wave could not been seen without significant amplification (100×). The strong non-dispersive slow waves were consistently observed in all samples and were confirmed as Biot’s slow waves because the propagation speeds were smaller than the acoustic sound speed in water. The slow wave speeds decreased with AVF and PPI, respectively. The attenuation increased with AVF and generally with PPI except for the 20 PPI samples where significant scattering and pulse-induced volume averaging might take place. The experimental and theoretical speeds were in agreement with a RMSE of 16 m/s (1%) for $n$ equal to 1.5. Above this value, the RMSE rose sharply. We conclude that the aluminum foams especially the 20 PPI samples have similar structural and ultrasonic properties to those of cancellous bone and thus have a good potential to become a bone-mimicking phantom. Future studies such as phantom anisotropy can further enhance our understanding of the phantom properties.

ACKNOWLEDGMENTS

This work was supported by a Discovery Grant (LL) from the Natural Sciences and Engineering Research Council.
APPENDIX A: FAST AND SLOW WAVE VELOCITIES IN BIOT’S POROUS MATERIALS

Following Williams (1992), the velocities of the fast and slow compressional waves travelling in liquid-filled porous materials are given, respectively, by

\[
V_{\text{fast,slow}}^2 = \frac{2(PR - Q^2)}{\Delta \pm \sqrt{\Delta^2 - 4(PR - Q^2)(\rho_{11}\rho_{22} - \rho_{12}^2)}}
\]

(A1)

and

\[
\Delta = P\rho_{22} + R\rho_{11} - 2Q\rho_{12}
\]

(A2)

where the parameters \( P, Q, \) and \( R \) are the modified elastic moduli:

\[
P = \frac{\beta(K_s - 1)K_b + \beta^2K_s + (1 - 2\beta)(K_s - K_b)}{1 - \beta - K_s^2 + \beta K_s K_b} + \frac{4\mu}{3},
\]

(A3)

\[
Q = \frac{(1 - \beta - K_s^2)\beta K_s}{1 - \beta - K_s^2 + \beta K_s K_b},
\]

(A4)

\[
R = \frac{K_s\beta^2}{1 - \beta - K_s^2 + \beta K_s K_b},
\]

(A5)

\( \beta = \text{the porosity}, \ K_s = \text{the bulk modulus of the fluid}, \ K_b = \text{the bulk modulus of the solid}, \) and \( \mu = \text{the bulk and shear moduli of the skeletal frame}. \)

The terms \( \rho_{11}, \rho_{12}, \) and \( \rho_{22} \) describe densities arising from the relative motion between solid and fluid and the interaction due to the inertial coupling:

\[
\rho_{11} + \rho_{12} = (1 - \beta)\rho_s,
\]

(A6)

\[
\rho_{12} + \rho_{22} = \beta\rho_f,
\]

(A7)

and

\[
\rho_{12} = (1 - \alpha)\beta\rho_f
\]

(A8)

where \( \alpha = \text{the tortuosity}. \)

For the cellular foam, the elastic moduli of the solid \( E_s \) and the frame \( E_f \) are related by a power law relationship (Williams, 1992)

\[
E^* = E_s(1 - \beta)^n
\]

(A9)

where \( n \) varies from 1 to 3 depending on the geometric structure of the solid frame and the ligament alignment with respect to the incident ultrasound beam (Gibson and Ashby, 1999). The moduli \( K_s, K_b, \mu, E_s, \) and \( E^* \) are related via the Poisson’s ratio of the solid \( (\nu_s) \) and the frame \( (\nu_b) \), respectively (Williams, 1992)

\[
K_s = Er_s/(1 - 2\nu_s),
\]

(A10)

\[
K_b = E^*/(1 - 2\nu_b),
\]

(A11)

and

\[
\mu = E^*/(2(1 + \nu_b))
\]

(A12)

where \( \nu_s = 0.33 \) (MatWeb) and \( \nu_b = 0.33 \) for open-celled foam (Gibson and Ashby, 1999).


MatWeb, Online materials information resource at http://www.matweb.com (Last viewed May 1, 2010).


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