Analysis of Homomorphic Processing for Ultrasonic Grain Signal Characterization

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Abstract—**As the ultrasonic signal passes through the material, signal energy is lost due to scattering and absorption. In large grained materials, such as polycrystallines, both scattering and absorption are functions of the frequency and grain size distribution. Grain scattering results in an upward shift in the expected frequency of a broadband ultrasonic echo, while the attenuation effect influences the frequency shift in a downward direction. These opposing phenomena can be utilized for grain size evaluation using the Fourier transform (FT) of the backscattered signal that consists of echoes with random amplitudes and phases corresponding to highly complex grain structures. Therefore, in order to estimate the spectral shift, some type of spectral smoothing operation is required. In the paper, homomorphic processing technique is evaluated for grain echo spectral-shift characterization. Computer simulation and experimental results obtained from heat treated steel and stainless steel samples with different grain sizes support the feasibility of using homomorphic processing for grain signal characterization.**

I. Introduction

IN RECENT YEARS ultrasonic spectrum analysis has been shown to be promising in both medical imaging and nondestructive testing (for example, see [1]–[12]). Often in testing materials nondestructively, spectrum analysis is used for characterizing the microstructure, flaw detection and sizing [1]–[5]. In medical imaging, spectrum analysis of scattered echoes has been useful in characterizing tissue and estimating the concentration of particles [6]–[12]. Lizzi *et al.* [9], [10] developed an analytical model of the power spectrum of broadband pulse system. This model is used in obtaining useful medical diagnostic parameters related to acoustical impedance and concentration of scatterers. The work of Kuc [11], [12] in medical imaging estimates the frequency of dependent attenuation from the spectral shift of the broadband reflected ultrasonic signal. Furthermore, he demonstrated the clinical potential of the spectral kurtosis as an additional parameter that can be employed for tissue characterization.

In the ultrasonic grain size characterization, a reasonably accurate model for the grain signal consists of the convolution of components representing the contributions of the measuring system impulse response (basic ultrasonic wavelet) and the grain scattering function. This function contains information related to many random physical parameters such as grain size, grain shape, grain orientation, quality of grain boundaries, and the proportion of chemical constituents [1], [13]. In order to quantitatively evaluate the inherent properties of the microstructure of the materials, it is desirable to decompose the measuring system impulse response and the grain scattering function. Conventional deconvolution techniques can be performed by inverse filtering or optimum zero-lag Wiener filtering. With these techniques the shape of the ultrasonic wavelet must be known or the assumption must be made that the wavelet is at minimum phase [14], [15]. Homomorphic deconvolution, a procedure for separating the components of the backscattered grain signal, requires the nonlinear processing of signals that have been combined in a nonadditive fashion. Homomorphic processing offers a considerable advantage in that no prior assumption about the nature of the ultrasonic wavelet or the impulse response of the transmission path is necessary. The ultrasonic wavelet recovered by homomorphic deconvolution is of importance in studies of regional attenuation and frequency dispersion in the backscattered grain signal spectrum. This paper presents an evaluation of homomorphic processing, which is capable of smoothing the power spectrum of the backscattered signal, and can be used for estimating the frequency shift resulting from grain scattering and attenuation. Both computer simulated data and experimental measurements are used for evaluating the performance of this technique.

A model for the amplitude of the backscattered signal, A_b, corresponding to a given depth z, can be described as [16]

$$A_b = A_0 \alpha_s(z, f)\, e^{-2\int_0^z \alpha(z,f)\,dz} \tag{1}$$

where A_0 is the initial amplitude, $\alpha_s(z, f)$ is the position and frequency-dependent scattering coefficient and $\alpha(z, f)$ is the overall attenuation coefficient. If materials exhibit homogeneous properties as a function of position z, then (1) can be simplified to

$$A_b = A_0 \alpha_s(f)\, e^{-2\alpha(f) z} \tag{2}$$

where $\alpha(f) = \alpha(z, f)$ and $\alpha_s(f) = \alpha_s(z, f)$. Note that the attenuation coefficient $\alpha(f)$ is a function of both the scattering coefficient $\alpha_s(f)$ and the absorption coefficient

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$\alpha_a(f)$

$$\alpha(f) = \alpha_a(f) + \alpha_s(f). \quad (3)$$

In general, grain scattering losses are large compared to absorption losses. The scattering coefficient has been classified based on the ratio of sound wavelength, λ, to the mean grain diameter, $\overline{D}$ [17]. When $\lambda > \overline{D}$ (Rayleigh scattering region), the scattering coefficient varies with the average volume of the grain ($\overline{D}^3$) and the fourth power of ultrasonic wave frequency, while absorption increases linearly with frequency. Hence, the attenuation coefficient can be represented in terms of the grain size and frequency

$$\alpha(f) = a_1 f + a_2 \overline{D}^3 f^4 \quad (4)$$

where a_1 is the absorption constant, a_2 is the scattering constant, and f is the wave frequency. Note that, for the scattering region in which the wavelength is of the same order as the grain diameter (Stochastic region), or is smaller than the grain diameter (Diffusion region), the scattering coefficient is less sensitive to the grain size or frequency [18]. Among the three scattering regions, Rayleigh scattering is of primary concern where multiple reflections between grain boundaries are negligible and $\alpha_s(f)$ shows high sensitivity to the variation in grain size.

In the Rayleigh scattering region, the scattering coefficient $\alpha_s(f)$ as a function of frequency ($f \propto \overline{D}/\lambda$) is shown in Fig. 1 [19], [20]. In this region, high frequency components are backscattered with larger intensity compared to low frequency components. Consequently, this situation results in an upward shift in the expected frequency of the power spectrum corresponding to the broadband echoes. The upward shift in frequency has been verified experimentally, and the results are presented in the experimental section. Since the spectral shift is grain size dependent, the estimate of the upward shift can be used for grain size characterization. Furthermore, inspection of (2) reveals that, the term $e^{-2\alpha(f)z}$ influences the frequency shift in a downward direction. The downward shift is dependent on the position of the scatterers relative to the transmitting/receiving transducer. The two opposing phenomena (i.e., upward shift due to scattering and downward shift caused by attenuation) can potentially be used for grain size evaluation. Estimating the frequency shift can only be achieved from random patterns of grain echoes, which is a challenging task. Nevertheless, techniques such as homomorphic processing can be utilized to smooth the power spectrum of the backscattered signal for frequency shift estimation in order to perform correlation studies between the estimated frequency shift and the inherent variation existing in the material's microstructure.

II. Spectral Analysis

The backscattered signal for a pulse–echo ultrasonic measurement of large grained samples consists of many interfering echoes with random amplitudes and arrival times. An example of backscattered signal from grains is shown in Fig. 2. The grain signal from a given region of the specimen can be represented as a convolution of the grain characteristics function, $g(t)$, and the impulse response of the measuring system, $\psi(t)$, which includes the attenuation characteristics of the propagation path

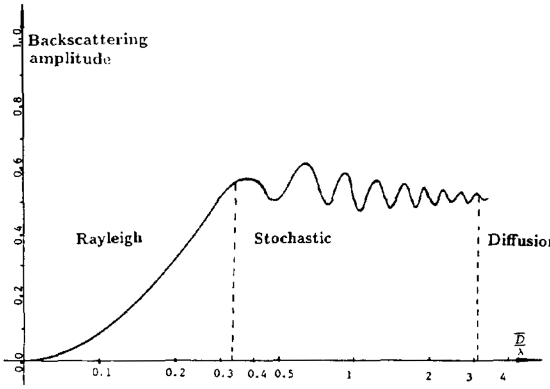

Fig. 1. Overall scattering behavior of ultrasound as function of normalized grain diameter ($\overline{D}/\lambda$).

$$r(t) = g(t) * \psi(t). \quad (5)$$

The $g(t)$ term is modeled as

$$g(t) = \langle \alpha_s(f) \rangle \sum_{k=1}^{N} \beta_k \delta(t - \tau_k). \quad (6)$$

The summation in (6) represents the composite nature of the backscattered echoes associated with grain scattering. The random variable N is the number of echoes with random arrival times, τ_k. The term $\langle \alpha_s(f) \rangle$ is the expected frequency-dependent scattering component of grains and β_k represents the intensity of the detected echoes.

The spectrum of the measured data can be obtained by taking a Fourier transform (FT) of (5)

$$R(f) = G(f)\Psi(f) \quad (7)$$

where

$$\Psi(f) = U(f)e^{-2\langle \alpha(f) \rangle z}. \quad (8)$$

The shape of $U(f)$ is governed by the transfer function of the ultrasonic pulser and the transmitting/receiving transducers. Since the measuring system characteristics are fixed, the function $U(f)$ is known and is often modeled as a bandpass Gaussian shaped spectrum. In practice, $U(f)$ can be measured using a flat surface reflector positioned at the far field of a transducer. The term $e^{-2\langle \alpha(f) \rangle z}$ is the frequency dependent attenuation corresponding to signal propagation of depth z through the material. Substituting (8) and the FT of (6) into (7) yields

$$R(f) = \left[\langle \alpha_s(f) \rangle e^{-2\langle \alpha(f) \rangle z} U(f) \right] \sum_{k=1}^{N} \beta_k e^{-j2\pi f \tau_k}. \quad (9)$$

Let us define

$$\langle U(f) \rangle = U(f)e^{-2\langle \alpha(f) \rangle z} \langle \alpha_s(f) \rangle \quad (10)$$

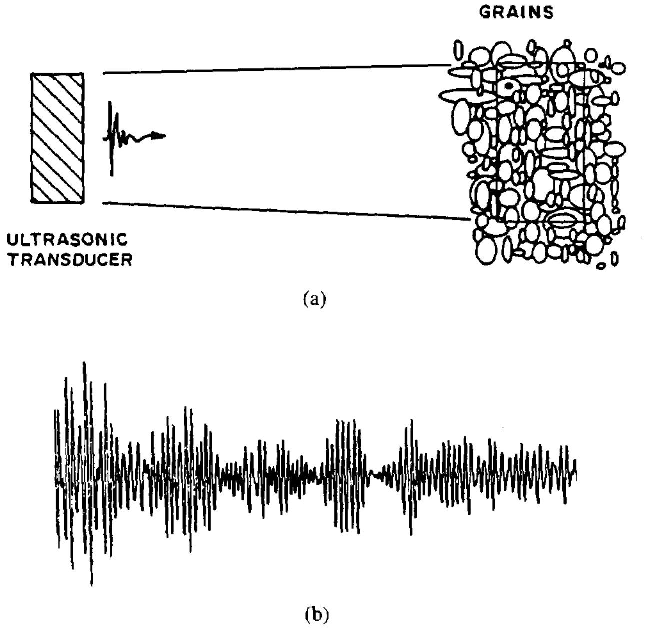

Fig. 2. (a) Range cell geometry. (b) Backscattered grain signal.

then,

$$R(f) = \langle U(f) \rangle \sum_{k=1}^{N} \beta_k e^{-j2\pi f \tau_k}. \quad (11)$$

In (11), the term $\langle U(f) \rangle$ consists of three functions: ultrasonic measuring system transfer function, $U(f)$, attenuation effect, $e^{-2\langle \alpha(f) \rangle z}$, and grain scattering effect, $\langle \alpha_s(f) \rangle$. All these functions are well-behaved and consequently, $\langle U(f) \rangle$ is a smooth function representing the frequency dependent attenuation and scattering effect of grains. In this paper, $\langle U(f) \rangle$ is referred to as the FT of the expected ultrasonic wavelet and depends on the physical characteristics of material. Note that, this function is modulated and distorted by the summation consisting of random terms as shown in (11). Since the term $\langle U(f) \rangle$ bears information related to the unknown physical parameters such as grain size, recovering $\langle U(f) \rangle$ from the random pattern of $R(f)$ becomes an important task.

An estimate of the FT of the expected ultrasonic wavelet $\langle U(f) \rangle$ can be achieved from $R(f)$ by a smoothing operation. The estimate, for example, may be obtained by measuring many signals and performing ensemble averaging on the corresponding power spectra. Although ensemble averaging is an effective method, it is not practical and limited by the correlation properties of multiple measurements [13]. Therefore, an alternative method that is capable of smoothing $R(f)$ with reasonable accuracy is desirable.

The frequency spectrum of the ultrasonic wavelet can be extracted from the measured signal through homomorphic processing [1]. The homomorphic wavelet recovery system is shown in Fig. 3(a). Figs. 3(b)–(f) represent processed signals at each step of Fig. 3(a). The magnitude spectrum of the grain signal (Fig. 3(c)) is obtained by Fourier transforming the measured grain signal (Fig. 3(b)). The logarithmic operator is used for converting the multiplicative relationship between the magnitude of $|\langle U(f) \rangle|$, and the random sum caused by grain scattering (11), to an additive relationship (Fig. 3(d)). The inverse Fourier transformation of Fig. 3(d) results in the grain signal magnitude cepstrum, $\hat{r}(t)$ (Fig. 3(e)). The wavelet magnitude cepstrum generally has a time width that is narrower than the terms resulting from grain scattering. Therefore, when a shortpass window (i.e., shortpass lifter) of duration equivalent to the echo duration is applied to the grain signal magnitude cepstrum, the magnitude cepstrum of the wavelet can be recovered. Finally, the FT of the wavelet's magnitude cepstrum will result in a Log spectrum (Fig. 3(f)), which yields the magnitude spectrum of the ultrasonic wavelet when an exponential operation is performed. The recovered magnitude spectrum of the wavelet is suitable for grain size characterization by estimating the frequency shift. Note that a challenging aspect of the homomorphic wavelet recovery system is the design of the shortpass lifter. An evaluation of the shortpass lifter design is presented in the next two sections.

Features such as the power-spectrum centroids of the spectrum of the recovered wavelet can be used for evaluating the spectral shift which leads to grain size characterization [21]. The power spectrum centroids, $\langle f_c \rangle$ are defined as

$$\langle f_c \rangle = \frac{\int_{\Delta f} f \left| \langle U(f) \rangle \right|^2 df}{\int_{\Delta f} \left| \langle U(f) \rangle \right|^2 df} \quad (12)$$

where Δf is the frequency range of the recovered echoes with high signal-to-noise ratio (SNR). In this paper, the power spectrum centroid is utilized for evaluating the performance and effectiveness of homomorphic processing in recovering the magnitude spectrum of the ultrasonic wavelet.

III. Evaluation of Spectral Smoothing Using Simulated Data

The object of computer simulation is to generate grain signals that mimic the behavior of random multiple interfering echoes and frequency contents of the measured grain signal. The grain signal is simulated by superimposing multiple echoes with random positions and amplitudes. Note that for the purpose of evaluating the smoothing capability of homomorphic processing, we have simulated signals based on the mathematical model shown in (11). In particular, the results associated with the three sets of data are presented here. It is assumed that for each case the FT of the expected ultrasonic wavelet, $\langle U(f) \rangle$, is Gaussian in shape, but with different center frequency, f_c, and bandwidth parameter, γ,

$$\left| \langle U(f) \rangle \right| \propto e^{-\gamma (f - f_c)^2}. \quad (13)$$

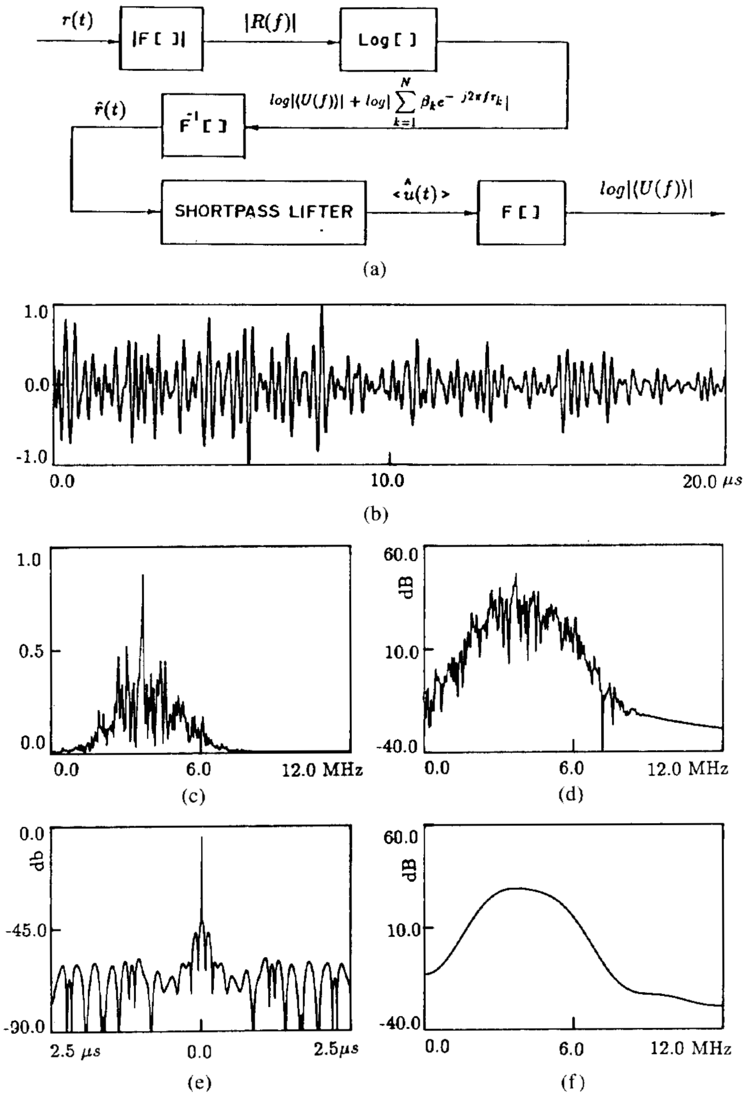

Fig. 3. Homomorphic wavelet recovery system. (a) System diagram. (b) Backscattered grain signal. (c) Magnitude spectrum of signal (b). (d) Log magnitude spectrum of signal (b). (e) Magnitude cepstrum of signal (b). (f) Recovered log magnitude spectrum of ultrasonic wavelet.

The center frequencies for these wavelets are 4, 4.5, and 5 MHz with 3-dB bandwidths of 1.25, 1.5, and 1.7 MHz, respectively. The simulated data consists of 2048 points with 100 MHz sampling rate. The entire simulated signal is formed by superimposing 512 detected random echoes in the duration of 20 μs. To determine the intensity of the detected echoes, a random number generator with Rayleigh probability distribution is used [13]. In addition, a uniformly distributed random number generator is used for determining the position of the scatterers.

The Rayleigh distributed random number generator was obtained by applying the following procedure. Two successive random numbers u and v uniformlyly distributed between (0, 1) are generated by a multiplicative congruential method [22]. Then, through the mathematical expressions [22]

$$s_{n-1} = \sigma\sqrt{-2 \log u} \cos 2\pi v + \mu \tag{14}$$

$$s_n = \sigma\sqrt{-2 \log u} \sin 2\pi v + \mu \tag{15}$$

where the random numbers u and v are transferred to uncorrelated Gaussian distributed numbers s_n and s_{n-1}, with mean μ and standard deviation σ. In this transformation process, the Gaussian distribution is assumed to have a mean of $\mu = 0$ and a standard deviation of $\sigma = 1$. Finally, the Rayleigh distributed random number is obtained by taking the square root of $s_{n-1}^2 + s_n^2$.

The simulation of the backscattered echoes has produced results very similar to the actual grain signals in terms of the random nature of signals and the frequency shift. The uniqueness of each data set, which coincides with the randomness of different measurements of the same materials, are observed (An example is shown in Fig. 4(b)). Homomorphic processing is applied to grain signals in order to obtain the expected magnitude spectrum of the ultrasonic wavelet, $|\langle U(f)\rangle|$. The spectra of the simulated grain signals are passed through the logarithmic operator to convert the multiplicative relationship between the Fourier transform of the expected echo

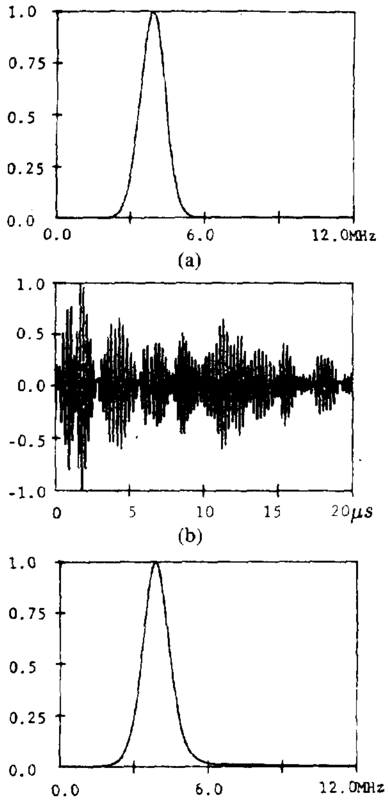

Fig. 4. Computer simulated grain signal. (a) Spectrum of 4-MHz center frequency wavelet. (b) Grain signal generated by 4-MHz wavelet. (c) Spectrum of recovered wavelet from grain signal.

wavelet and the random sum to the additive relationship

$$\log \left|R(f)\right| = \log \left|\langle U(f)\rangle\right| + \log \left|\sum_{k=1}^{N} \beta_k e^{-j2\pi f\tau_k}\right|. \tag{16}$$

The cepstra of the simulated grain signals are obtained using the inverse Fourier transform of (15). The length of the shortpass lifter is 64 sample points corresponding to 0.64 μs. The shortpass lifter is applied to the cepstrum of the grain signals to recover the magnitude spectrum of wavelets corresponding to the original echoes. Note that the recovered magnitude spectrum (Fig. 4(c)) is very similar to the actual simulated magnitude spectrum (Fig. 4(a)).

For the purpose of evaluating the smoothing capability of homomorphic processing techniques, the center frequencies of the three estimated wavelets are compared with the corresponding actual wavelet center frequencies of 4, 4.5, and 5 MHz. The power spectrum centroids were calculated using (12) and the results are presented in Table I. Table I shows the quantitative error of the estimates are very small and less than 2 percent. These results are encouraging and reveal that the cepstral smoothing is indeed very effective. In fact, the differences in the estimates of $\langle f_c \rangle$ show a clear sensitivity to the changing center frequency of the wavelet. It should be noted that the choice of time-width for the shortpass lifter is essential in obtaining a good estimate. A short duration shortpass lifter will truncate information at the cepstrum domain, and consequently, the recovered wavelet will have a broad-band spectrum. On the other hand, a long duration shortpass lifter will introduce spurious information in the cepstrum domain that may distort the recovered wavelet.

TABLE I
POWER SPECTRUM CENTROIDS FOR SIMULATED GRAIN SIGNALS

Actual Center Frequency of Reference Wavelet	Estimated Center Frequency of Recovered Wavelet $\langle f_c \rangle$	Error
4.0	4.06	1.5 percent
4.5	4.56	1.3 percent
5.0	5.07	1.4 percent

IV. Discussion of Shortpass Lifter

The most important step in homomorphic wavelet recovery is the design of the time windows (shortpass lifters) in the cepstrum domain. The word "lifter" originated by Bogert *et al.* [23], and is the paraphrased term, according to a syllabic interchange rule, for the word "filter," which stands for the filter in the cepstrum domain. The basic function of the shortpass lifter is to filter out the effect of the random pattern associated with the detected grain echoes so as to make wavelet recovery possible. However, since shortpass lifter behavior is analogous to that of the lowpass filter, the shape and duration of the shortpass lifter (time-pass) are the key parameters in deciding the performance of the homomorphic wavelet recovery system. Hence, it is necessary to discuss the choice of relevant parameters of the shortpass lifter so that the best performance can be achieved.

It has been observed that the cepstrum amplitude of the grain signal varies significantly with time. In particular, the amplitude of the cepstrum segment corresponding to the wavelet is generally much larger than the remaining segments corresponding to the grains. Therefore, information in the neighborhood of the largest peak area is of primary concern. A comparison of a wavelet magnitude cepstrum and a grain signal magnitude cepstrum for simulated signals is shown in Figs. 5(a) and (b), respectively. Inspection of this figure reveals that a window of short duration centered in the neighborhood of the largest peak in Fig. 5(b) will extract the information associated with the wavelet and eliminate the remaining random variation caused by the scattering of echoes resulting from the microstructure of the material. It must be noted that broad duration shortpass lifters will introduce spurious patterns in the recovered spectrum of the wavelet. Furthermore, a narrow duration shortpass lifters will truncate the necessary information for wavelet recovery, and the bandwidth of the recovered wavelet will be larger than the original one [24]. Therefore, optimization of the duration of the shortpass filter is an essential operation of wavelet recovery.

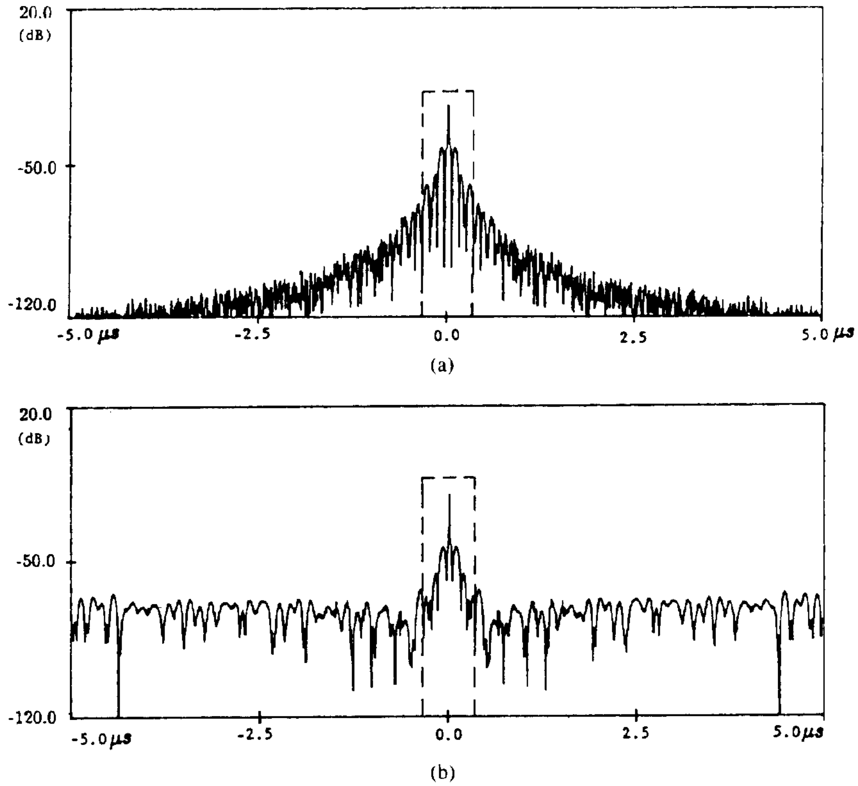

Fig. 5. Magnitude cepstrum of computer simulated data in logarithmic scale. (a) Wavelet. (b) Grain signal.

Accurate wavelet recovery is important in attenuation or frequency shift estimation and any minor distortion of the spectrum of the recovered wavelet can result in significant errors in estimation. Fig. 6 displays the recovered magnitude spectrum for the same simulated wavelet using different duration of rectangular shortpass lifters. In this computer simulation, the center frequency of the ultrasonic wavelet is 5 MHz, and the bandwidth of the wavelet is 2.5 MHz. Fig. 6(a) shows the spectrum of the recovered wavelet when the duration of the shortpass lifter is 2.56 μs. Since the duration of the shortpass lifter is slightly longer than the wavelet duration, the recovered wavelet spectrum displays spurious patterns due to grain characteristics. Fig. 6(b) shows the spectrum of the recovered wavelet when the duration of the shortpass lifter is 1.28 μs. Clearly, the shortpass lifter eliminates the effect of the grain characteristic function and results in a smooth recovered wavelet spectrum. Fig. 6(c) and 6(d) show the spectra of the recovered wavelet when the duration of the shortpass lifter is 0.64 μs and 0.32 μs, respectively. These results reveal that when the duration of the shortpass lifter is too short, the bandwidth of the recovered wavelet becomes large, thus adversely affecting the estimate of power spectrum centroids. In fact, Fig. 6(d) shows that when the duration of the shortpass lifter is 0.32 μs, the bandwidth of the recovered wavelet is enlarged by about 20 percent.

Based on extensive computer simulations, it was determined that for best results the shortpass lifter should have a duration equivalent to the duration of the actual wavelet, that is inversely proportional to the signal bandwidth. A comparison of cepstra in logarithmic scale corresponding to wavelets with identical center frequencies, but different bandwidths is shown in Fig. 7. In this figure, the center frequency is 5 MHz and the bandwidths are 1.5 MHz (Fig. 7(a)), 2.0 MHz (Fig. 7(b)) and 2.5 MHz (Fig. 7(c)). Comparison of the results shown in Figs. 7(a)–(c) indicates that the duration of power cepstrum of the signal is roughly the same as the duration of the wavelet in time domain. Therefore, the best performance for homomorphic wavelet recovery system is achieved when the duration of the shortpass lifter varies inversely with the signal bandwidth, or directly with the echo timewidth.

It is important to note that when a window is applied to data, the spectrum of the original signal gets distorted by the characteristics of the window. The rectangular window used in this study is simple to implement, and its effect is easy to evaluate. However, other types of windows may perform satisfactorily for the homomorphic wavelet recovery system. As an alternative, the Gaussian type window was examined in this study. Fig. 8(a) shows the results of applying the Gaussian type window to the cepstrum of the signal. As with the rectangular window, the width of the Gaussian window is an important factor in obtaining an accurate recovered wavelet. If the width of the Gaussian window is greater than the expected

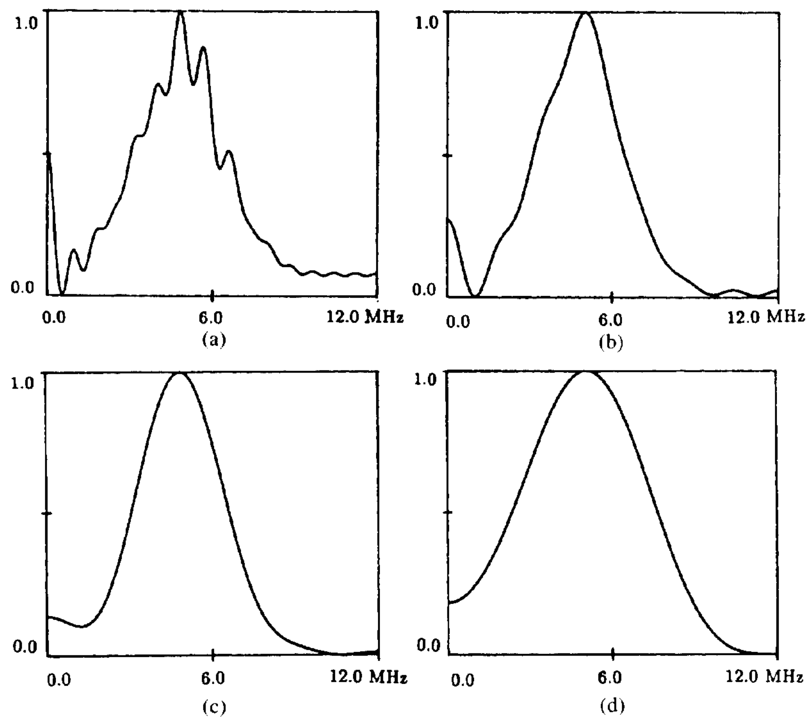

Fig. 6. Effect of rectangular shortpass lifter duration on simulated signal with center frequency of 5 MHz and bandwidth of 2.5 MHz. (a) 2.56 μs. (b) 1.28 μs. (c) 0.64 μs. (d) 0.32 μs.

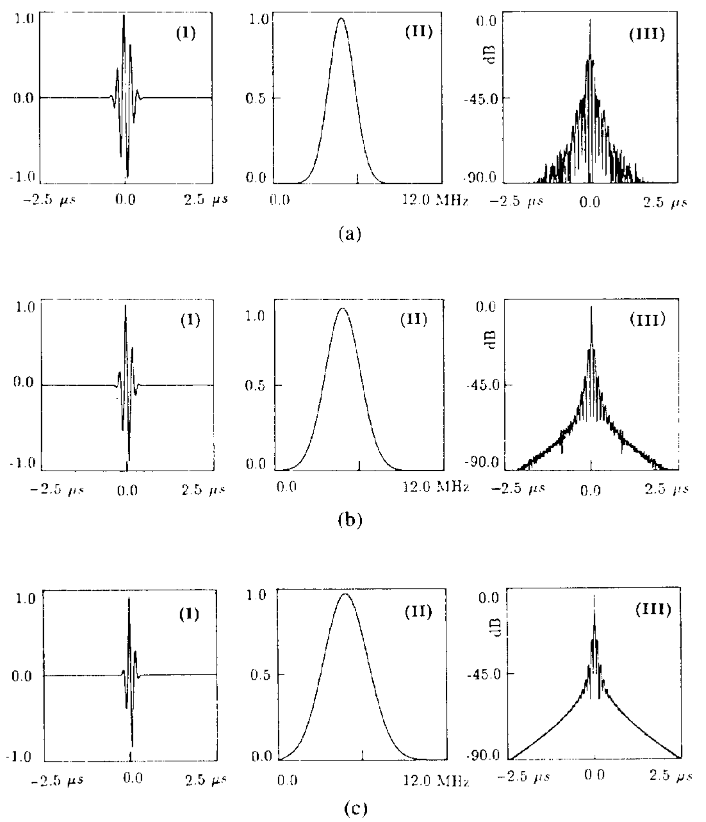

Fig. 7. Comparison of different timewidth (or bandwidth) wavelets and their magnitude spectra and cepstra. I is wavelet. II is magnitude spectrum of wavelet. III is power cepstrum for wavelet. (a) 1.5-MHz bandwidth wavelet. (b) 2.0-MHz bandwidth wavelet. (c) 2.5-MHz bandwidth wavelet.

wavelet duration, the recovered wavelet begins to be influenced by grain characteristics. If the width of the Gaussian window is less than the expected wavelet duration, the shape of the recovered wavelet power spectrum becomes broader, which will increase the error when estimating the power spectrum centroids. For optimal results the width of the Gaussian window must be close in measurement to the duration of the wavelet. Figs. 8(b)–(d) display the magnitude spectra of the recovered wavelets using Gaussian windows with 3-dB timewidths of 0.45 μs, 0.25 μs and 0.13 μs. Clearly, the choice of the timewidth of the window will dictate the quality of the estimates.

Both rectangular and Gaussian windows are capable of recovering the wavelet with reasonable accuracy. The results reported here indicate that the rectangular window performs slightly better (in terms of the estimation accuracy for the power spectrum centroids of the wavelet) compared to the Gaussian window. It has been observed that in the region where the power cepstrum of the wavelet is very small (60 dB below its maximum value) the cepstrum of grain characteristics is at least 30 dB higher than the cepstrum of the wavelet. The rectangular window can eliminate the grain characteristics information completely while the Gaussian window is not capable of total elimination since its tail will always pass some grain signal (for clarity, refer to Fig. 5). Consequently, the wavelet recovered using the rectangular window has less grain signal than the wavelet obtained using the Gaussian window.

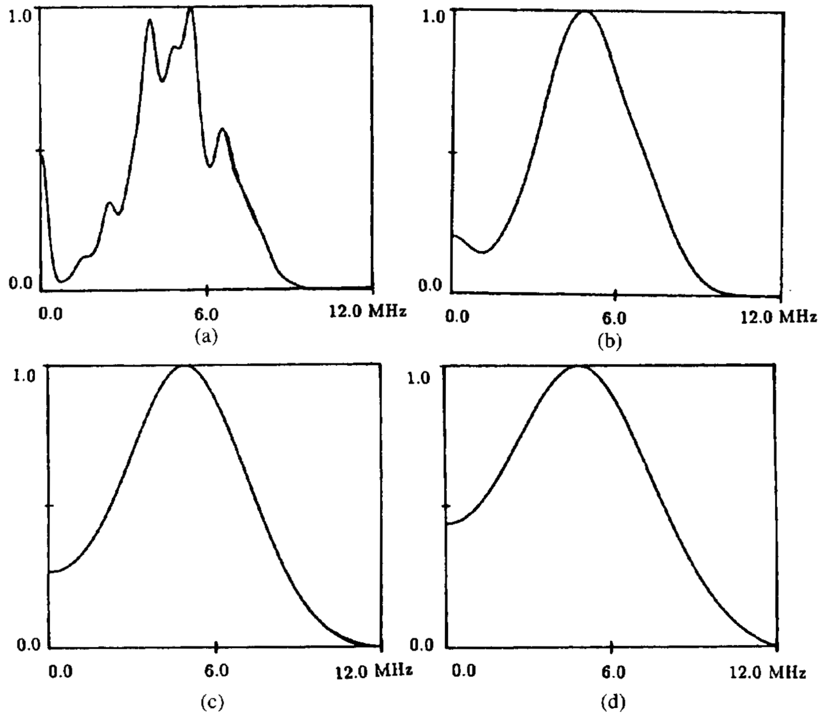

Fig. 8. Effect of Gaussian shortpass lifter duration of simulated signal with center frequency of 5 MHz and bandwidth 2.5 MHz. (a) At 1.35 μs. (b) At 0.45 μs. (c) At 0.25 μs. (d) At 0.13 μs.

V. Experimental Results and Discussion

The experiments were conducted using a Panametrics transducer with 6.22-MHz center frequency and 3-dB bandwidth of 2.75-MHz. Both steel blocks and stainless steel rods with different grain sizes were examined. The steel blocks are type 1018. The initial grain sizes (prior to heat treatment) were 14 μm. Two of steel blocks were heat treated at 1700°F and 2000°F, that increased the average grain sizes to 25 μm and 50 μm, respectively. The specimens were placed at the far field of the transducer and the ultrasonic measurements were performed using an immersion testing technique. The transducer impulse response, that serves as the reference ultrasonic wavelet in comparing the upward and downward shift in the processed spectrum, was measured using the flat surface echo from one of the specimens (see Fig. 9).

The grain signals shown in Fig. 10 have a 20 μs duration corresponding to grain scattering from within a region of 1 cm to 7 cm inside the steel specimens. As noted earlier, there will be an inherent upward shift in the expected frequency of the grain signal due to scattering, and a downward shift caused by the attenuation effect. In all the measured grain signals, it was observed that the upward shift in the frequency is far more dominating than the downward shift. The quantitative value of the power spectral centroids are presented in Table II. As shown in this table, all materials exhibit an upward shift in the frequency due to the scattering effect compared to reference echo. However, since attenuation begins to dominate as the grain size increases, the degree of upward shift is reduced with respect to the reference signal for larger grained samples. For example, steel–2000 (the specimen with the largest grains) shows a lower upward frequency shift than the other two samples. Note that steel–1700 shows a slightly higher upward frequency shift in the expected frequency than the "steel" specimen, which is inconsistence with the model prediction. This discrepancy may be caused by the estimation error and/or the possible inherent variations in the scattering properties of the grains.

It should be noted that the differences in the expected frequencies of the steel samples are minimal since the ultrasonic wavelength is about 1000 μm, and the $\overline{D}/\lambda$ values for all the specimens are small (steel: $\overline{D}/\lambda = 0.014$; steel-1700: $\overline{D}/\lambda = 0.024$; steel–2000: $\overline{D}/\lambda = 0.050$) such that they correspond to the lower and insensitive portion of the Rayleigh scattering region (for clarity, refer to Fig. 1). Also, the bandwidth limitations imposed by the transducer can alter the frequency shift caused by grain scattering, thus contributing to the reduction in the expected frequency shift.

To further demonstrate the correlation between the upward shift in the expected frequency and the grain size, the experimental measurements were repeated using stainless steel samples with more significant variation in grain size. These samples are 2-in diameter stainless steel rods with average grain sizes of 25 μm, 86 μm and 160 μm. These specimens were studied using the same transducer as before, resulting in the experimental data presented in Table III. It is clear that these specimens exhibit upward frequency shift, which is much more noticeable and consistent with the effects of scattering the attenuation compared to the steel samples (i.e., the specimen with

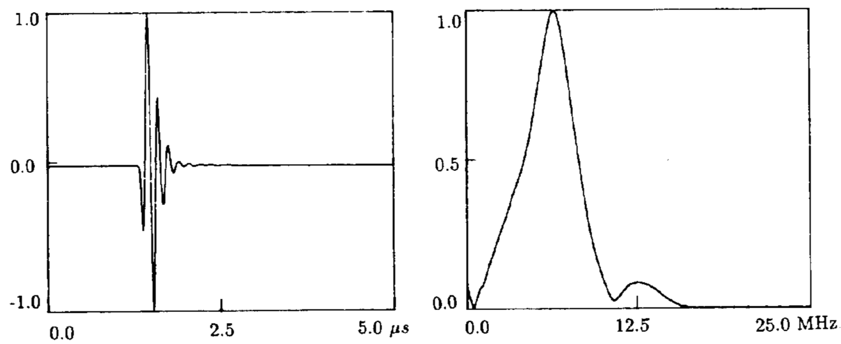

Fig. 9. Impulse response and magnitude spectrum of transducer.

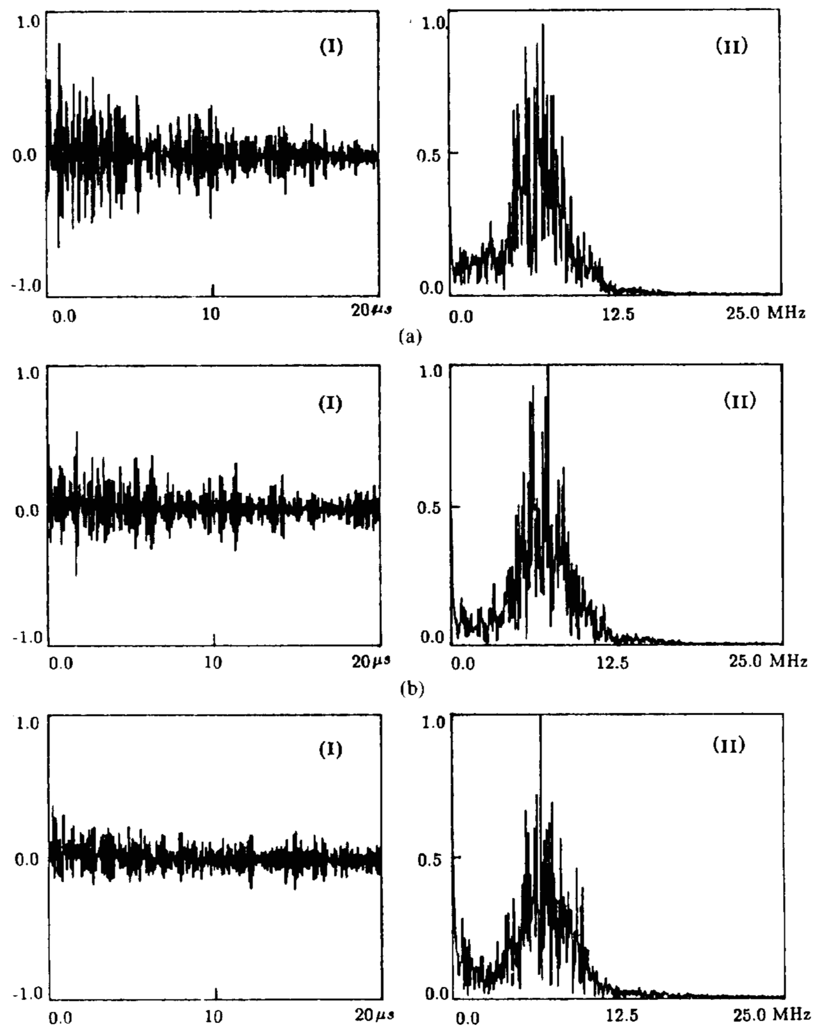

Fig. 10. Grain signals of steel specimens. I shows grain signal. II shows magnitude spectrum. (a) Steel-2000. (b) Steel-1700. (c) Steel.

TABLE II
UPWARD FREQUENCY SHIFT OBSERVED FOR GRAIN SIGNALS FROM STEEL SPECIMENS

Sample	Grain Size	Estimated Frequency ⟨ f_c ⟩
Reference echo	—	6.22 MHz
Steel	14 μm	6.868 MHz
Steel-1700	25 μm	6.881 MHz
Steel-2000	50 μm	6.667 MHz

TABLE III
UPWARD FREQUENCY SHIFT OBSERVED FOR GRAIN SIGNALS FROM STAINLESS STEEL SPECIMENS

Sample	Grain Size	Estimated Frequency ⟨ f_c ⟩
Reference echo	—	6.22 MHz
SS	25 μm	7.34 MHz
SS-1350	86 μm	6.90 MHz
SS-1387	172 μm	6.67 MHz

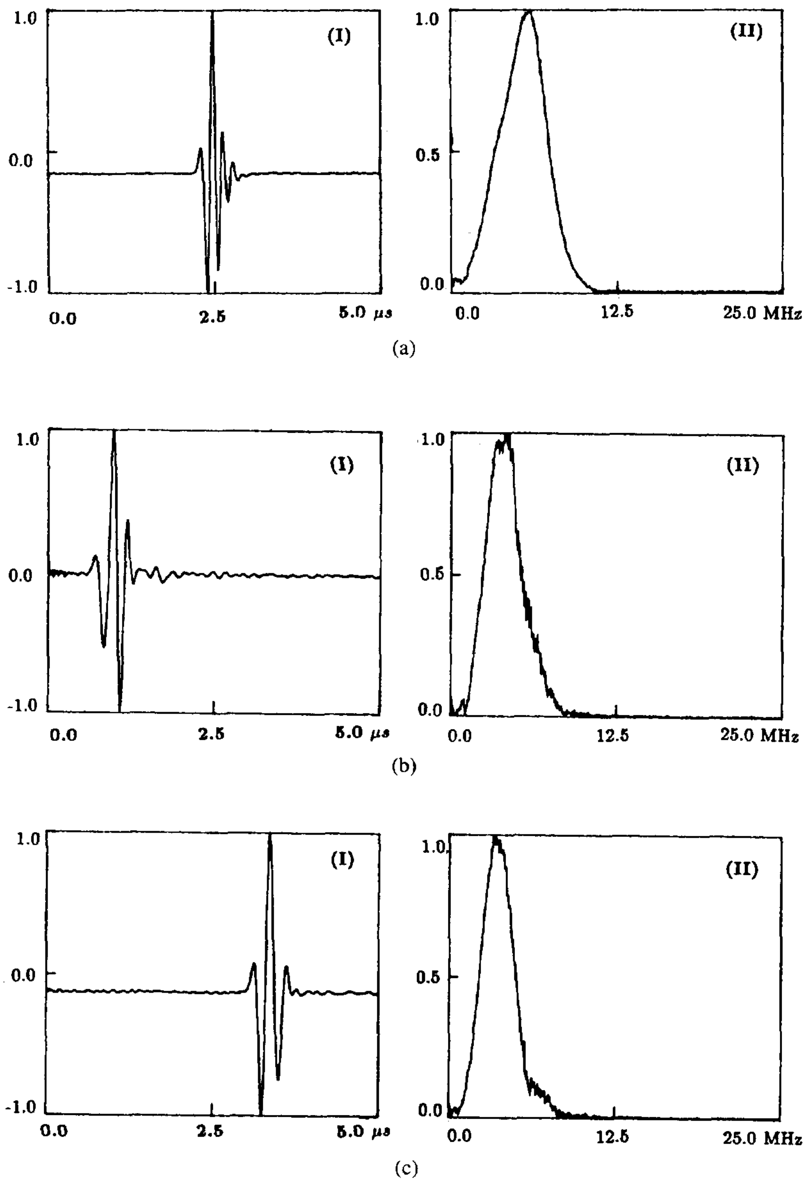

Fig. 11. Backsurface echo of steel specimens. I shows backsurface echo. II shows magnitude spectrum. (a) Steel-2000. (b) Steel-1700. (c) Steel.

larger grain size has lower upward shift in frequency compared to the reference echo).

To assess the degree of downward frequency shift caused by attenuation, the backsurface echoes of the steel samples were examined (see Fig. 11). The backsurface echo spectra shown in Fig. 11 exhibit the downward frequency shift introduced by attenuation as a result of the ultrasonic signal traveling through an 8-in distance in the steel samples (i.e., round trip distance between the front and back surfaces). The computed power spectrum centroids are listed in Table IV. The expected frequency has been shifted from 6.22 MHz for the reference signal, to 5.63 MHz, 4.26 MHz, and 4.02 MHz for the "steel," "steel-1700," and "steel-2000" samples, respectively. These results clearly support the high degree of correlation between the grain size and the estimated frequency shift due to attenuation.

TABLE IV
DOWNWARD FREQUENCY SHIFT OBSERVED FROM BACK-SURFACE ECHOES USING STEEL SPECIMENS

Samples	Grain Size	Estimated Frequency $\langle f_c \rangle$
Reference echo	—	6.22 MHz
Steel	14 μm	5.63 MHz
Steel-1700	25 μm	4.26 MHz
Steel-2000	50 μm	4.02 MHz

VI. CONCLUSION

In this paper, a model for the grain signal has been presented, which includes the effect of frequency dependent scattering and attenuation. This model predicts that the expected frequency increases with scattering and decreases with attenuation. Homomorphic processing was used for spectral smoothing and the selection of parameters for optimal performance was examined. Experimental results presented here display both the upward shift in the expected frequency with grain boundary scattering and the downward shift with attenuation. Furthermore, it has been shown that the expected frequency shift can be correlated with the grain size of the material. It is important to point out that the quantitative relationship between the average grain size and the expected frequency shift (either upward or downward) is dependent on the type of material, the quality of grain boundaries, as well as the characteristics of the measuring instruments. Therefore, proper interpretation of the presence or absence of frequency shift in the measured data needs to be carefully examined prior to its application to grain size characterization.

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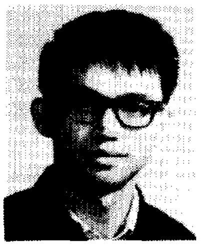

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