SPECTRAL EVALUATION OF ULTRASONIC GRAIN SIGNALS**

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ABSTRACT

The ultrasonic wave traveling through solids is subject to energy losses due to scattering and absorption. In the Rayleigh scattering region, both scattering and absorption are functions of frequency and grain size distribution. Grain scattering results in an upward shift in the expected frequency of a broadband ultrasonic wave , while the attenuation effect influences the frequency shift in a downward direction. These opposing phenomena can be utilized for grain size evaluation. In this report, we present a spectral-shift quantization technique using homomorphic processing and moment analysis. Computer simulation and experimental results obtained from steel samples with different grain sizes support the feasibility of using spectral quantization techniques for grain size characterization.

## I. INTRODUCTION

Conventional ultrasonic microstructure evaluation techniques are based on a comparison of attenuation measurements of specimens with unknown grain sizes to specimens with known grain sizes. This is accomplished either by transmitting an ultrasonic wave through the specimen using two transducers, or by pulsing the transducer and measuring the amplitude of the echo as it returns from the far end of the specimen toward the transducer. An alternative method of estimating attenuation is by using frequency domain information of the backscattered grain signal. Since attenuation is a function of frequency and grain size distribution, a broad-band transducer can be used to measure the backscattered signal and to perform spectral analysis. In this paper we present an evaluation of two techniques for spectral analysis, moment estimation and homomorphic processing, the processes of which were presented in our earlier work [1]. These techniques are capable of estimating frequency shift resulting from grain scattering and attenuation in the power spectrum. Both computer simulated data and experimental measurements are used for evaluating the performance of these techniques.

A model for the expected amplitude of the backscattered signal, $A_b$, corresponding to a given position $z$, is:

$$A_b = A_o \alpha_s(z,f) e^{-\int_o^z \alpha(z,f)dz} \quad (1)$$

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where $A_o$ 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, Eq. 1 can be simplified to:

$$A_b = A_o \alpha_s(f) e^{-\alpha(f)z} \quad (2)$$

where $\alpha(z,f) = \alpha(f)$ and $\alpha_s(z,f) = \alpha_s(f)$. Note that the attenuation coefficient $\alpha(f)$ is caused by the scattering coefficient $\alpha_s(f)$ and absorption $\alpha_a(f)$:

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

In general, grain scattering losses are large compared to absorption losses. The scattering coefficient has been classified based on the ratio of sound wavelength, $\lambda$, to the mean grain diameter, $\overline{D}$ [2]. For the situation where $\lambda > \overline{D}$ (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 is increased linearly with the frequency. Hence, the attenuation coefficients can be represented in terms of 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 larger than the grain diameter Diffusion region), the scattering coefficient is far less sensitive to the grain size or to the frequency[2].

The overall $\alpha_s$ behavior as a function of the normalized grain diameter ($\frac{\overline{D}}{\lambda}$) is shown in Fig. 1 [3,4]. Among the three scattering regions, Rayleigh scattering where multiple reflections between grain boundaries are negligible and $\alpha_s(f)$ shows high sensitivity to the grain size variation is of primary concern. In the Rayleigh scattering region, high frequency components are backscattered with large intensity compared to low frequency components. Consequently, this situation results in an upward shift in the expected frequency of the power spectrum of broadband echoes. In fact, the frequency upward shift behavior can be verified , and results are presented in the experimental section. Since the degree of the spectral shift is grain size dependent an estimate of upward shift can be used for grain size characterization. Furthermore, inspection of Eq. 1 reveals that, the term $e^{-\alpha(f)z}$ 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. Therefore, a family of curves, as shown in Fig. 2 for different positions of scatterers, must be considered for frequency shift evaluation. The two opposing phenomena (i.e., upward shift due to scattering and downward shift caused by attenuation) can be utilized to our advantage for grain size evaluation. Estimating frequency shift can only be achieved from random patterns of grain echoes, and this is a challenging task. Nevertheless, techniques such as homomorphic processing and moment analysis can be used to quantize the frequency shift in the power spectrum in order to perform correlation studies between the estimated frequency shift and the variation existing in the material's microstructure.

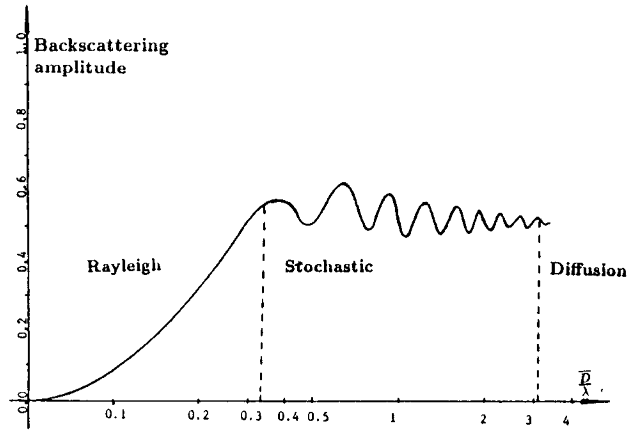


Fig. 1 The overall scattering behavior as a function of the nomalized grain diameter ($\frac{\overline{D}}{\lambda}$).

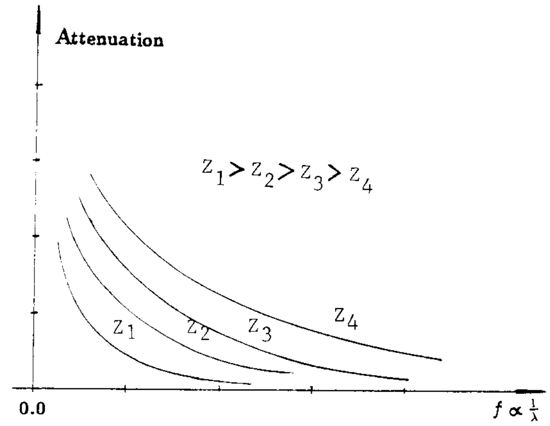


Fig. 2 Attenuation as a function of the frequency and position.

## II. SPECTRAL ANALYSIS

The backscattered grain signal from a given region of the specimen (e.g., j-th region) can be modeled as a convolution of the mean ultrasonic wavelet, $< u_j(t) >$, and grain characteristic function, $g_j(t)$:

$$r_j(t) = < u_j(t) > * g_j(t) \tag{5}$$

where

$$g_j(t) = \sum_{k=1}^{N_j} A_{kj}\delta(t - \tau_{kj}) \tag{6}$$

The term $< u_j(t) >$ represents the mean shape of the echo (i.e., impulse response of the transducer or wavelet) within the j-th region of the sample. The shape of this function is governed by transfer functions of the ultrasonic pulser, transmitting and receiving transducers, amplifier, and the variable propagation path characteristics. Since the measuring system characteristics are fixed, any change in the ultrasonic wavelet is indicative of the acoustical properties of the propagation path. In the above equations, the random variable $N_j$ represents the number of scatterers in the j-th region, the random variable $A_{kj}$ represents the scattering cross-section of grains caused by the quality of grain boundaries, shape, size and the proportionality of chemical constituents [5]. The random variable $\tau_{kj}$ represents the random position of the grain scattering centers in the j-th region of the specimen.

The spectrum of the measured data corresponding to the j-th region can be obtained by Fourier transforming Eq. 5:

$$R_j(f) = G_j(f) < U_j(f) > \tag{7}$$

where

$$G_j(f) = \sum_{k=1}^{N_j} A_{kj} e^{-2\pi i f \tau_{kj}} \tag{8}$$

The grain transfer function $G_j(f)$ has a complicated form consisting of random amplitudes and phases corresponding to highly complex grain structures. This function modulates and distorts the magnitude spectrum of the wavelet, $< U_j(f) >$, which results in the frequency shift. Since the frequency shift phenomenon bears information related to the unknown physical characteristics of the specimen such as grain sizes, it is possible to classify the samples with different grain sizes by quantitatively evaluating the frequency shift appearance.

The term $R_j(f)$ consists of random patterns and an estimation of $< U_j(f) >$ from $R_j(f)$ can only be achieved by performing some sort of smoothing operation. For example, measuring many signals and performing ensemble averaging of the power spectra can result in an estimation of the power spectrum of the wavelet. Ensemble averaging is an effective method but not practical. Therefore, any alternative method which is capable of smoothing of $R_j(f)$ with reasonable accuracy is always 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. As shown in this figure, the magnitude spectrum of the grain signal is obtained by Fourier transforming the backscattered signal. The logarithmic operator is used for converting the multiplicative relationship between the wavelet and the grain impulse response to the additive relationship. The inverse Fouier transform results in the grain signal power cepstrum, $\hat{r}_j(t)$. The wavelet power cepstrum generally has a time width which is narrower than that of the grain impulse response. Therefore, when a shortpass window (i.e. shortpass lifter) of a duration equivalent to the echo duration is applied to the grain signal power cepstrum, the power cepstrum of the wavelet can be recovered. Finally, the Fourier transform of the wavelet's power cepstrum will result in a *Log* spectrum and when an exponential operation is performed at this stage, it generates the magnitude spectrum of the ultrasonic wavelet. The recovered magnitude spectrum of the wavelet can be used to estimate frequency shift for grain size characterization. Note that a challenge aspect of the homomorphic wavelet recovering system is the design of the shortpass lifter. An evaluation of such a design is presented in the computer simulation section.

A comparison of the regional estimate of an ultrasonic wavelet results in an estimation of frequency-dependent attenuation. For example, from knowledge of an ultrasonic wavelet corresponding to two successive regions of the specimen seperated by $\Delta d$, the frequency-dependent attenuation coefficient can be estimated [1]:

$$\alpha_j(f) = \frac{log| < U_j(f) > | - log| < U_{j+1}(f) > |}{\Delta d} \qquad (9)$$

An alternative method which is simple to implement and has the potential to characterize the presence of a frequency shift in an ultrasonic backscattered signal is moment analysis[6]. A generalized definition for moments is given:

$$\overline{M}_{KL} = \frac{\int_0^\infty f^K |R_j(f)|^L df}{\int_0^\infty |R_j(f)|^L df} \qquad (10)$$

Due to the integrating operation which is inherent to moment estimation, the contribution of the random pattern of the power spectrum to moment values is less noticeable compared to the effect of a frequency shift. A confirmation of this statement has been evaluated using extensive computer simulation (results are presented later). When $L = 1$ and $K$ is a positive integer, then $\overline{M_{1K}}$ is the $K$th moments of the magnitude spectrum according to the common definition of moments. In general, $K$ and $L$ can be any real number. The usefulness of the above equation becomes apparent only if the moment results show enough correlation to an unknown physical characteristic such as the grain size. For the special case in which $K = 1$ and $L = 2$,

$$\overline{M}_{12} = \frac{(\int_0^\infty f|R_j(f)|^2 df)}{(\int_0^\infty |R_j(f)|^2 df)} \qquad (11)$$

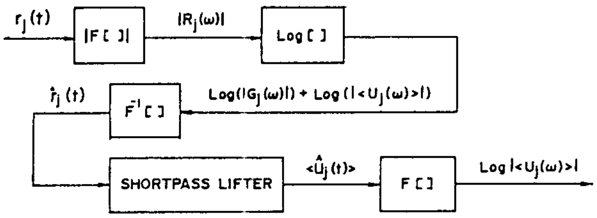


Fig. 3 Homomorphic wavelet recovery system.

the $\overline{M}_{12}$ is referred to as the power spectrum centroids. In our earlier studies[6], the examination of the moment values (K=1, 2, 3, and L= 1,2,3,4) revealed that no specific feature in the magnitude spectrum ( e.g., a forbidden band of frequency or an enlarged frequency component) existed. Therefore, no unusual value has been observed (either very large or very small) for the moments of a higher order of weighing. In addition, a noticeable correlation has been found to exist among moments corresponding to different values of $K$ and $L$. Hence, it becomes evident, for our present studies, that one moment (e.g., power spectrum centroids) is adequate for quantizing the magnitude spectrum.

## III. COMPUTER SIMULATION

The object of computer simulation is to reproduce grain signals with the same behavior of random multiple interfering echoes and frequency content as the measured grain signal. Then, the simulated grain signal can be utilized to examine the effectiveness and sensitivity of homomorphic processing and moment analysis schemes. The key parameter of the model is frequency shift, and it is varied for simulating ultrasonic grain signals.

Spectrum analysis techniques are applied to extract the frequency shift from simulated data. The grain signal is simulated by superimposing multiple echoes with random positions and random amplitudes. It is assumed that the mean ultrasonic wavelets are Gaussian in shape with center frequencies 4, 4.5 and 5 MHz and 3 dB bandwidths of 1.25, 1.5 and 1.70 MHz, respectively. The entire generated signal is made up of 2048 points with a 100 MHz sampling rate. It is also assumed that about 512 random echoes will be detected by the transducer in the duration of 20 $\mu s$ of the backscattered signal. To depict the size of the detected echoes, a random number generator with a Rayleigh probability distribution is used. In addition, a uniformly distributed random number generator is used for determining the position of the scatterers. There are three sets of data generated (using different sets of random numbers), each of them has a different center and bandwidth (see Fig. 4a, d and g). The grain signals has been obtained by a convolution of the grain characteristic function $g_j(t)$ and the ultrasonic wavelet $< u_j(\cdot) >$.

The simulation of the backscattered echoes has produced signals very similar in terms of their random nature

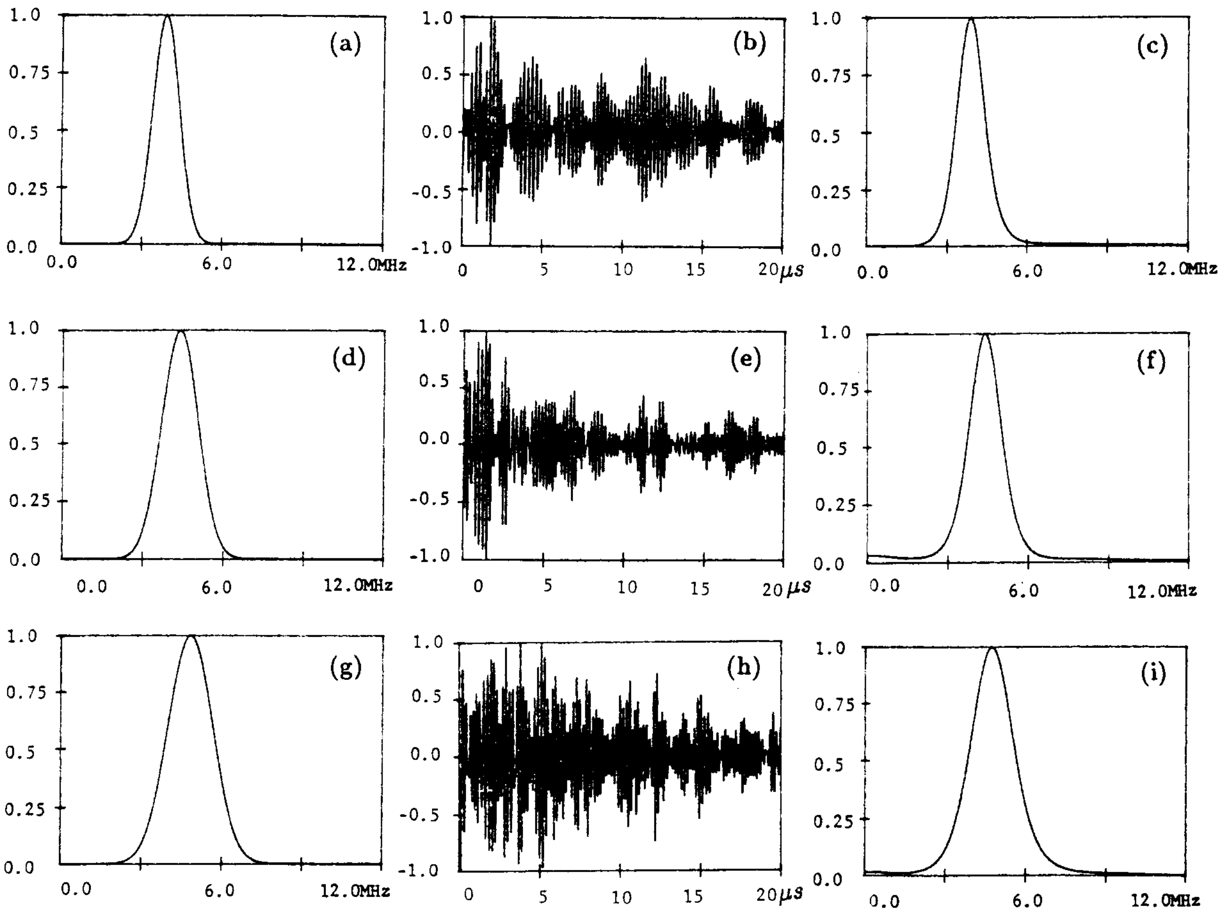


Fig. 4 Computer simulated grain signals

a) spectrum of a 4 MHz center frequency wavelet.

b) grain signal produced by 4 MHz wavelet.

c) spectrum of recovered wavelet from the grain signal(a).

d) spectrum of a 4.5 MHz center frequency wavelet.

e) grain signal produced by 4.5 MHz wavelet.

f) spectrum of recovered wavelet from the grain signal (e).

g) spectrum of a 5 MHz center frequency wavelet.

h) grain signal produced by 5 MHz wavelet.

i) spectrum of recovered wavelet from the grain signal (h).

and frequency shift to that of actual grain signals. The uniqueness of each data set, which coincides with the randomness of different measurements of the same materials, is easily observed (Fig. 4b, e and h). Homomorphic processing is applied to grain signals in order to obtain the basic ultrasonic wavelet. The spectra of the simulated grain signals were passed through the logarithmic operator to convert the multiplicative relation between the mean echo wavelet and the grain characteristic function to the additive relation:

$$log|R_j(f)| = log| < U_j(f) > | + log|G_j(f)| \qquad (12)$$

The cepstrums of the simulated grain signals were obtained using an inverse Fourier transform of Eq. 12. The length of the shortpass lifter was 64 sample points corresponding in time to about 0.64$\mu s$. The shortpass lifter was applied to the cepstrum of the grain signals and the wavelets corresponding to the original echoes were recovered (see Fig. 4c, f and i).

For the purpose of evaluating the sensitivity of homomorphic processing techniques, we have compared the three sets of data with their respective center frequencies: 4, 4.5 and 5 MHz. Moment estimation of the spectrum from different data sets specifies the frequency shift as discussed earlier. The power spectrum centroids defined in Eq. 11 are calculated and presented in Table I. The differences in the moment estimation of the spectra show a clear sensitivity to the changing center frequency of the wavelet, but some error must be anticipated due to the random patterns of the spectrum of each data set. As we noted, there are

| Actual center frequency of the echo (MHz). | Center frequency estimated from the grain sigal (MHz). | Error |
|---|---|---|
| 4.05 | 4.06 | 0.25% |
| 4.55 | 4.56 | 0.24% |
| 4.99 | 5.07 | 1.6% |

Table I. The power spectrum centroids of the simulated grain signals.

some variations in recovered wavelets and the power spectrum centroids, however, a number of studies reveal that such variations are small. In fact, Table I shows that the quantitative errors are less than 2%. It should be noted that the choice of length for the shortpass lifter is essential for obtaining a good estimate. A short duration of the 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 of the shortpass lifter will introduce spurious information in the cepstrum domain which may distort the recovered wavelet.

## IV. EXPERIMENTAL RESULTS & DISCUSSION

The experiments were conducted using a Panametrics transducer with 6.22 MHz center frequency and 3-dB bandwidth of 2.75 MHz. Two specimens examined in this study were steel blocks type 1018. One steel block has an average grain size of $14\mu m$. The other block was heat-treated at a temperature of $2000^oF$ and the average grain size of the sample grew to 50 $\mu m$. The specimens were placed at the far fields of the transducer and the ultrasonic measurements were performed using the immersion testing technique. The transducer impulse response, which serves as the reference ultrasonic wavelet for the comparison of the upward and downward shift in spectrum, was measured using the front surface echo of the specimen (see Fig. 5 ). The grain signal shown in Fig. 6a with a $20\mu s$ duration contains the information corresponding to grain scattering within the region of 1 $cm$ to 7 $cm$ of the steel specimen. It must be noted that inherent to any grain signal is an upward shift in frequency due to scattering, and a downward shift caused by an attenuation effect. In all measured grain signals, we have observed that the upward shift in the frequency is far more dominanting than the downward shift. In order to assess the degree of downward shift caused by the microstructures of materials, the backsurface echo was measured (see Fig. 6b). The result shown in Fig. 6b, displays the downward shift effect introduced by attenuation since the echo is backscattered from the far end flat surface of the specimen (no scattering effect). Figure 7 shows the measured grain signal spectrum and its wavelet recovered

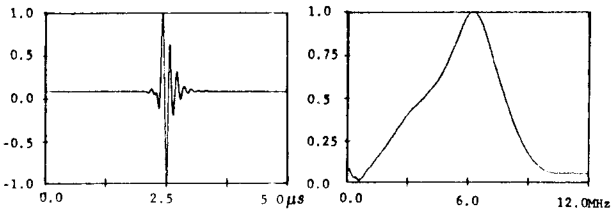


Fig. 5 The transducer impulse response and its amplitude spectrum.

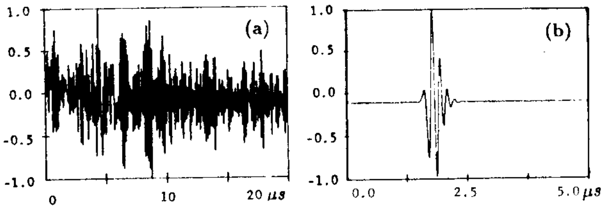


Fig. 6 a) The grain signal measured from a steel sample.
b) The backsurface echo measured from a steel sample.

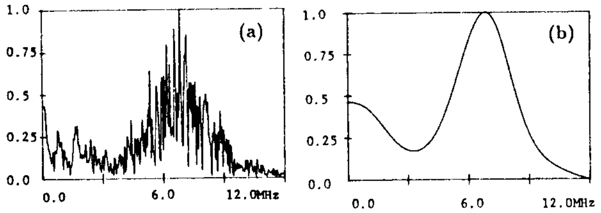


Fig. 7 a) The spectrum of the measured grain signal from a steel sample.
b) The spectrum of the recovered wavelet from the grain signal of a steel sample.

through homomorphic processing. The estimated power spectrum centroids for the transducer impulse response, recovered grain signal wavelet and the backsurface echo are 6.22 MHz, 7.02 MHz and 5.94 MHz, respectively. These results demonstrate the existance of an upward frequency shift due to scattering and a downward frequency shift due to attenuation. The degree of frequency shift can be correlated to the inherent properties of the grain scattering.

Similar experimental measurements were conducted using the heat-treated steel sample (steel-2000). Figure 8 shows the backscattered grain signal and the backsurface echo of the steel-2000 specimen. The spectra of the grain signal and the recovered wavelet are shown in Fig. 9. The estimated power spectrum centroids for the recovered wavelet and the backsurface echo are 6.62MHz and 4.54 MHz, respectively. Comparison of the power spectrum cen-

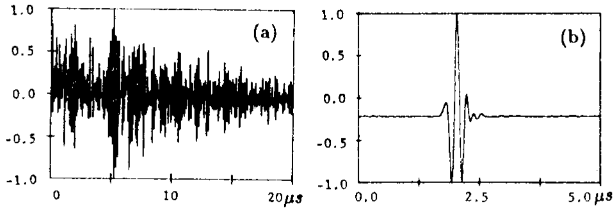


Fig. 8 a) The grain signal measured from a steel-2000 sample.

b) The backsurface echo measured from a steel-2000 sample.

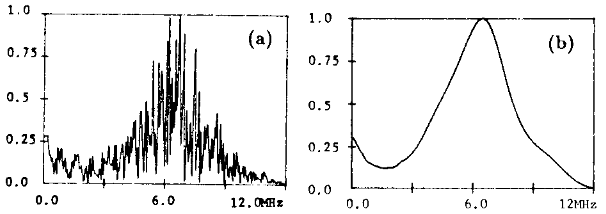


Fig. 9 a) The spectrum of the measured grain signal from a steel-2000 sample.

b) The spectrum of the recovered wavelet from grain signal of a steel-2000 sample.

troids from the grain signals using 'steel' and 'steel-2000' indicate that the difference in frequency shift is relatively small, although 'steel' has a much smaller grain size than that of the 'steel-2000' specimen. The lack of a significant frequency shift may be accounted for since the ultrasonic wavelength is about $1000\mu m$, and $\frac{\overline{D}}{\lambda}$ for both specimens is so small (steel: $\frac{\overline{D}}{\lambda} = 0.014$; steel-2000: $\frac{\overline{D}}{\lambda} = 0.050$) that they fall into the lower and insensitive portion of the Rayleigh scattering region (for clarity, refer to Fig. 1). Furthermore, the measuring transducer has a limited bandwidth and filters out the desirable frequency shift caused by grain scattering which can also account for an insignificant frequency shift.

In summary, upward and downward shifts of frequency are inherent properties of the ultrasonic wave propagating through a random medium. Homomorphic processing and moment analysis are effective techniques in estimating that frequency shift in order to evaluate the microstructure of materials. Experimental results using steel samples presented in this paper suggest the feasibility of using these techniques in non-destructive testing.

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