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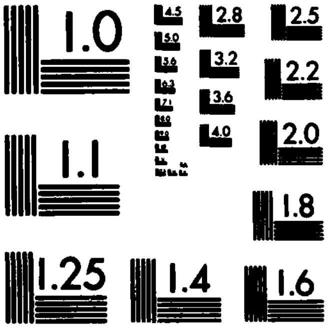
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The objective of this research program was to develop a technique to nondestructively measure average grain size as a function of position and to also provide some measure of the size distribution of the scatterers. To nondestructively evaluate the microstructure, the material was probed using broad-band ultrasound. The resulting backscattered ultrasound echoes were then processed to obtain the required microstructure parameters by applying techniques adapted from our previous work on Flaw Enhancement in large grain materials. Previous —

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work on nondestructive microstructure evaluation has centered on obtaining a single parameter related to the average grain size in a relatively large volume of material. In contrast, this research effort was directed toward evaluating the local microstructure of the material as function of position. This does not imply a point-by-point mapping of grain size, but rather the evaluation of grain statistics within small volumes of the bulk material.

Final Report

AFOSR Grant No. AFOSR-81-0177

For the period: 06/01/81 to 08/31/82

GRAIN STRUCTURE IDENTIFICATION
by
ULTRASOUND FREQUENCY AVERAGING AND DECONVOLUTION

prepared for

AFOSR/NE Electronics Division

by

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July 1983

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CONTENTS

INTRODUCTION

Currently there exists no technique for nondestructively determining the microstructure for any given region within bulk material. Although grain size, porosity, and inclusions are dominant factors in determining the structural properties of materials, these parameters must be deduced from surface measurements or destructive testing of similar samples. The wide spread use of heat treatments to change structural properties and welds to join material, the introduction of brittle alloys and structural ceramics have all contributed to the growing need for nondestructive microstructure evaluation throughout the entire volume of a structural member.

The importance of microstructure evaluation has been recognized by research groups in both the United States and Europe. Using ultrasound to probe the internal structure of the material these workers have sought to obtain a parameter characteristic of the average bulk material properties. Although this approach may be ideal for process control during the initial stages of material preparation, average values and gross parameters are not adequate for evaluation of the structural integrity of structural elements. The results of this previous work will be reviewed in more detail in the following section.

The thrust of this research effort was directed toward the evaluation of local microstructure parameters. As in previous research on nondestructive microstructure evaluation, our approach relies on the use of ultrasound to probe the interior of the material. The back-scattered echoes resulting from the interaction of the transmitted ultrasound with the local microstructure contain a wealth of information about the size, nature, and distribution of the microstructure. By collecting these echoes and separately processing the signals from small regions of the bulk, it should be possible to characterize the local properties of the microstructure. The success of this approach hinges on the effective utilization of signal processing techniques developed over the past several years, principally for use in radar systems, to extract the desired microstructure parameters.

In addition to actually determining microstructure parameters, the results of this program will also bear on the problem of unambiguously identifying target location in highly reverberant structures. When using pulse echo ultrasound to examine highly reverberant structures containing partially reflecting interfaces, such as the edges of welds, the beam pattern becomes so complicated that the arrival time of an echo no longer provides a true and unambiguous indication of its point of origin. In most materials the echo from an interface is accompanied by much smaller 'grass-like' echoes from the grain structure. If it were possible to relate this 'grass' to the grain structure at its point of origin, then the origin of the larger associated interface echo could be unambiguously identified in those cases where the regions between the various reflecting interfaces have different grain structures.

BACKGROUND

Most of the previous work on nondestructive evaluation of grain size has been carried out in Germany and was directed toward development of process controls for steel and stainless steel production. For these applications, it is generally accepted that ultrasound is the most appropriate means of probing grain structure since the sound is effectively scattered by both grain boundaries (elastic anisotropy) and phase boundaries (impedance discontinuities). Consequently, for thick steel samples, with thicknesses in the range of several inches to several feet, the effects of ultrasound scattering are easily observed.

The original work on grain size estimation using back-scattered ultrasound was performed by Fay (1973). Using the fact that the intensity of the transmitted ultrasound wave decays in amplitude with depth, due to material absorption and scattering, Fay was able to demonstrate that the rate of decay of back-scattered echoes as a function of depth was related to the grain size of the metal. Further, he demonstrated that this relationship could be used to monitor changes in the average grain size from one steel billet to another.

To obtain an estimate of the average grain size using this method, a narrow-band ultrasounic pulse is transmitted into the sample and the resulting back-scattered signals recorded. Next, a second narrow-band ultrasonic pulse of a different frequency, is transmitted into the material and its echoes recorded. By plotting the average amplitude of the echoes as a function of depth for the two signals, it is possible to separate the attenuation effects due to material loss from those due solely to grain boundary scattering. Finally the average grain size is estimated by comparing the measured grain scattering coefficient with the scattering coefficients obtained from standard samples of known grain size.

This technique relies on an assumption of uniform average grain size and distribution along the entire sound path. To accurately measure the attenuation coefficients, the data must also be recorded over a fairly long acoustic path within the metal. Since the parameter estimation is based directly on the acoustic path length, single scattering must also be assumed. This requires that the scattering be weak, due either to small impedance changes at the grain boundaries or the use of ultrasound which has a wavelength that is long compared to the average grain size. These factors limit the application of this technique to rather general estimates of grain size within a large sample volume.

A refinement of Fay's technique was developed by Goebbels (1978). To more accurately determine the amplitude of the back-scattered echoes as a function of depth, Goebbels applied spatial averaging. By recording the grain echoes produced along several acoustic paths within the material and averaging, the random variation of the echo amplitude due to the individual grains could be effectively reduced. Thus the accuracy with which the attenuation, and consequently the scattering coefficient, could be measured was significantly increased.

Although this variation of the back-scattering technique for grain estimation improved the reliability of the measurement and somewhat reduced the required length of the acoustic path within the material, the resulting estimate of average grain size still applied to a substantial volume of the material. In this case, the averaging takes place not only in the axial direction along the ultrasonic beam path, but also in the transverse plane.

The previously described techniques for measurement of grain size in steel have recently been extended for use in the production of rolled steel plates by Hecht et al. (1980). To obtain a sufficiently long propagation path within the plate, "leaky' surface acoustic waves were used. As these ultrasonic waves propagate along the surface of the sheet, echoes are returned from the grain boundaries in a manner very similar to those produced by bulk waves. Processing these back-scattered echoes as described above has been shown to yield sufficient information about the average grain size to provide the basis for controlling the heat treatment during rolling of the steel sheets.

During the last several years, a considerable effort directed toward the study of individual, isolated scatterers has been sponsored by DARPA. The principal goal of these scattering studies, conducted by Rockwell International and Stanford, was to extract more information from the ultrasound back-scattered by inclusions, voids, and cracks in high temperature structural ceramics. It was hoped that sufficient information could be obtained to allow the size, shape, orientation, and nature of the defect to be defined. Although certainly of interest, these studies have little bearing on the evaluation of grain structure and therefore will not be considered further.

More closely related to the topic of grain estimation is the NASA funded work of O'Donnell et al. (1980) on ultrasonic scattering from random distributions of spheres.

The work reported to date focuses on broad-band ultrasonic back-scattering from dilute random distributions of uniform glass spheres embedded in hardened polyester resin. For at least the case of weak scattering from dilute distributions, it is possible to establish an accurate analytic models to describe the back-scattered echo amplitude. Preliminary measurements seem to be in good agreement with these models.

Although the study of dilute distributions of scatterers is far removed from the case of densely packed grains, it is extremely encouraging that in this study the size of the glass spheres could be deduced through the use of broad-band ultrasound. This work seems to clearly indicate that the back-scattered echoes of a broad-band ultrasonic pulse contain sufficient information to characterize the microstructure within any given region of a sample. Thus the challenge that remains is to extract this information.

PROGRAM OVERVIEW

RESEARCH OBJECTIVES

The objective of this research program was to develop a technique to nondestructively measure average grain size as a function of position and to also provide some measure of the size distribution of the scatterers. To nondestructively evaluate the microstructure, the material was probed using broad-band ultrasound. The resulting back-scattered ultrasound echoes were then processed to obtain the required microstructure parameters by applying techniques adapted from our previous work on Flaw Enhancement in large grain materials (Bilgutay et al. 1982).

Previous work on nondestructive microstructure evaluation has centered on obtaining a single parameter related to the average grain size in a relatively large volume of material. In contrast, this research effort was directed toward evaluating the local microstructure of the material as function of position. This does not imply a point-by-point mapping of grain size, but rather the evaluation of grain statistics within small volumes of the bulk material.

The ability to evaluate microstructure in relatively small areas of metal or ceramic samples is expected to have many applications. For example, areas of improper heat treatment could be readily detected or anomalies in the heat affected zone of welds, characteristic of structural weakness, could be identified. Porosity in cast metals or pressed ceramics could be characterized to determine their effect on structural integrity or subsequent machining. Identification of local microstructure could also serve as a valuable aid in unambiguously locating defect sites in structures of complicated geometry.

The first year of this program was devoted exclusively to the case of weak scattering, for which the individual scatterers (grains) are assumed to be much smaller than the acoustic wavelength and the back-scattered signals result entirely from single scattering events. During this year the theory relating the back-scattered ultrasonic signals to the grain structure was established and the necessary algorithms for efficiently extracting the required microstructure parameters were developed. In addition, suitable samples were prepared to experimentally evaluate the performance of the signal processing techniques. For reasons discussed in the Summary, the actual experimental evaluation of the signal processing techniques developed during this program for microstructure parameter estimation has not been carried out.

DIVISION OF TASKS

For the period: 06/01/81 to 12/31/81

PURDUE UNIVERSITY

- Determine the Characteristic Lattice Spectrum for one-dimensional Quasi-periodic and Aperiodic scatterer distributions.
- Computer simulate the calculated Characteristic Lattice Spectra.
- Computer simulate the back-scattered ultrasonic echoes from typical Quasi-periodic and Aperiodic lattice structures.
- Extract the known lattice parameters from the simulated back-scattered ultrasonic signals.

For the period: 01/01/82 to 05/31/82

DREXEL UNIVERSITY

- Complete development of suitable algorithms for extracting microstructure parameters from experimental data.
- Extend theoretical calculations of Lattice Impulse Response toward more realistic model by including the effects of attenuation.

PURDUE UNIVERSITY

- Prepare and characterize suitable samples for evaluation of signal processing algorithms being developed under Drexel subcontract.
- Conduct experimental tests to verify performance of algorithms on real ultrasonic data.
- Modify signal processing algorithms as necessary to achieve reliable estimates of microstructure parameters.

Extension period: 06/01/82 to 08/31/82

PURDUE UNIVERSITY

- **Extension requested to allow time for experimental evaluation of parameter extraction algorithms due to delay in obtaining signal processing algorithms being developed under Drexel subcontract.**

LIST OF ACCOMPLISHMENTS

For the period: 06/01/81 to 12/31/81

- Calculation of the theoretical Characteristic Lattice Spectrum for sparse one-dimensional arrays of scatterers.
- Simulation of back-scattered ultrasonic echoes typical of several possible scatterer distributions.
- Recovery of the Characteristic Lattice Spectrum from simulated back-scattered ultrasonic echoes through the use of spatial averaging.

For the period: 01/01/82 to 05/31/82

- Extension of theoretical calculations to include the effects of attenuation on the Characteristic Lattice Spectrum.
- Investigation of several parameter estimation techniques to determine an efficient method of microstructure parameter estimation.
- Preparation and experimental evaluation of a variety of both sparse and dense scattering targets.
- Calculation of the statistics for the actual equivalent one-dimensional lattice from reported experimental measurements of actual grain size distributions.

GRAIN LATTICE IMPULSE RESPONSE

To calculate the echoes obtained by an ultrasound beam penetrating a grain lattice, consider Figure 1 which represents a section through the center of such a beam. We will make the simplifying assumption - to be relaxed later - that the grain lattice is perfectly regular. We will also assume - this can be done without loss of generality - that the ultrasound wavefronts are plane and normal to the beam edges, that the grain lattice has negligible thickness normal to the plane of the figure, and that the ultrasound back-scattering is produced by the grain corners which act as point reflectors. With these assumptions, the ultrasound echoes will be those due to a series of point reflectors, whose spacings can be calculated by projecting the grain corners onto a line parallel to the incident ultrasound beam. Projections for different beam directions are given in Figure 1. These projections are seen to be almost periodic, with each unit cell of a particular projection containing one or more scatterers depending on the angle between the projection and the lattice. It seems clear that the same situation will hold for a lattice of finite thickness and a beam of arbitrary cross-section, provided that the beam cross-section does not change with range.

For the remainder of this account we will restrict ourselves to projections with only one reflector per unit cell. We can then write the Grain Lattice Impulse Response which represents the spacing and amplitudes of the scatterers giving rise to the ultrasound echo, as

$$m(t) = \sum_{i=1}^{N} a_i \, \delta(t - \tau_i) \tag{1}$$

where τ_i is the ultrasound time of flight from the origin and back to the ith scatterer, and N is again the number of scatterers within the ultrasound range cell. The Lattice Impulse Response is seen to be analogous to the impulse response of a linear filter through which the transmitted ultrasound is passed to produce the back-scattered echo.

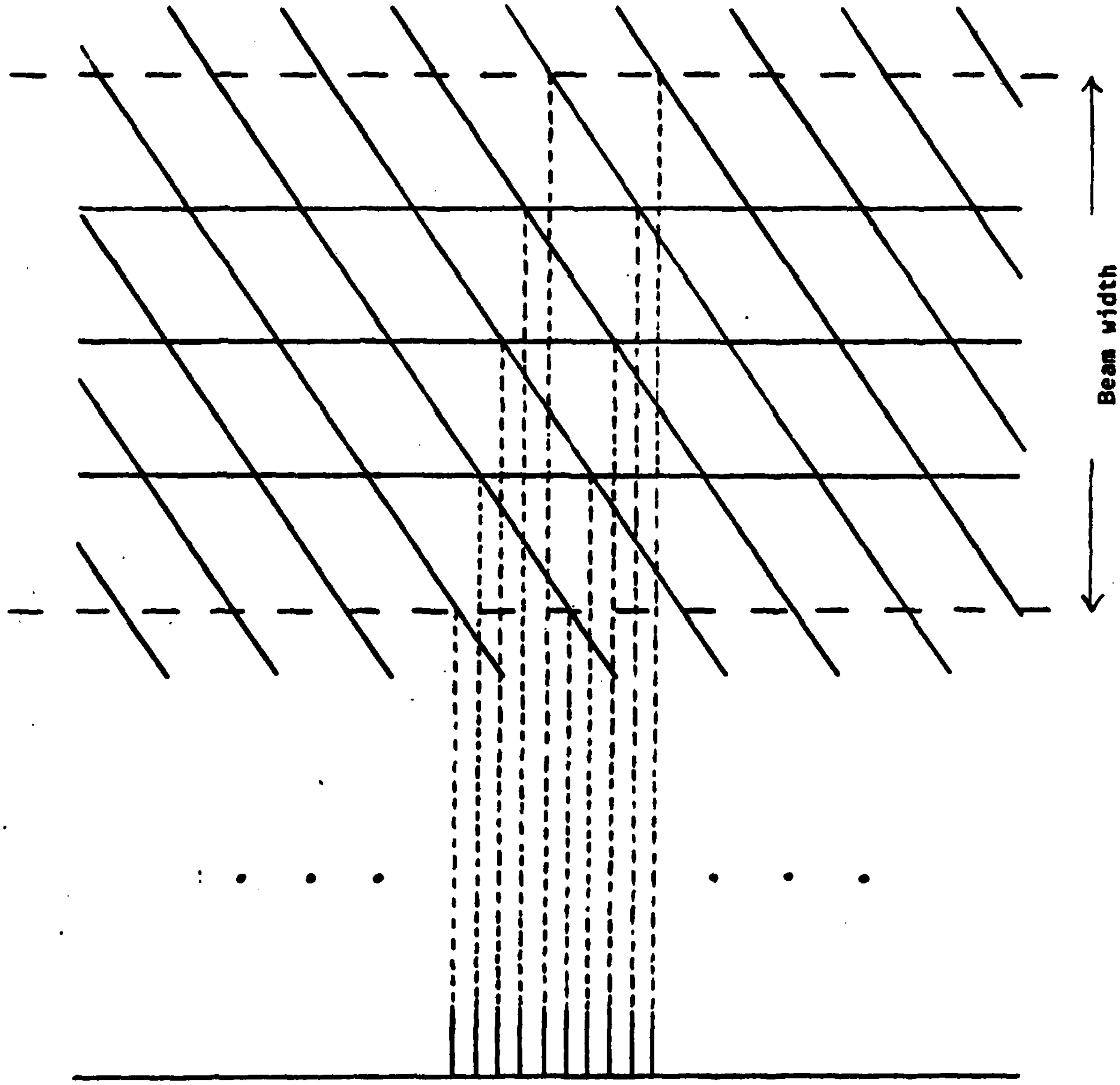


Fig. 1a. Periodic lattice with projections of scatterers along lattice symmetry axis.

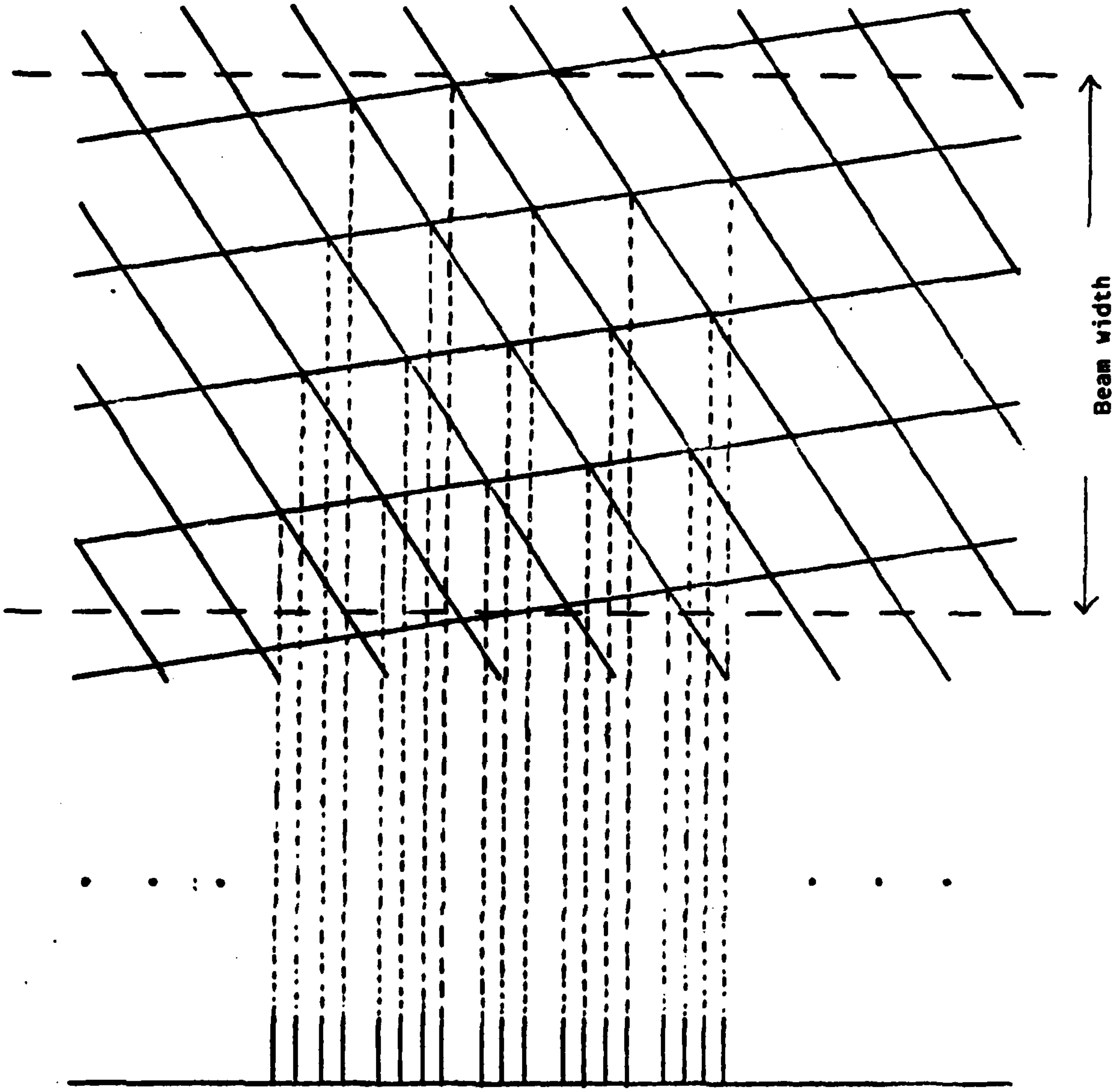


Fig. 1b. Projection along non-symmetry axis.

CALCULATION OF THE LATTICE SPECTRUM

REGULAR LATTICE

By Fourier transforming (1) we obtain what we will call the Grain Lattice Transfer Function

$$M(f) = \sum_{i=1}^{N} a_i \, e^{-j2\pi\tau_i f} \tag{2}$$

We will show that this function is related to the spectrum of the echo obtained from grainy materials. For scatterers of constant cross-section and uniform spacing $\Delta\tau$ it is shown by Newhouse et al. (1982) that (2) can be written as

$$|M(f)|^2 = a^2N^2 \operatorname{sinc}^2[\pi f/B] \tag{3}$$

where B is the bandwidth of the ultrasound transmitted signal which is related to the length L of the range cell by $L = c/2B$ and c is again the velocity of sound.

The magnitude of the Lattice Transfer Function M(f) is plotted in Figure 2 and is seen to vanish at $f = B, 2B, 3B$ etc. At these frequencies the length of the range cell is equal to an integral number of half wavelengths of the ultrasound center frequency, so that destructive interference occurs between scatterers at different points in the range cell.

This important result shows that the echo amplitude from a strictly periodic array of scatters vanishes due to interference, at an infinite series of frequencies related to the bandwidth or range cell length of the incident radiation. We will see below that similar but finite minima occur in the Lattice Transfer Function of non-periodic lattices, and that the height of these minima can be used to deduce the lattice parameters.

APERIODIC LATTICE

By this term we refer to a Lattice Impulse Response having one scatterer per unit cell, with the range x_i of the ith successive scatterer defined as a random variable whose value is uniformly distributed over the length L of the range cell. The scattering amplitude a_i of the ith scatterer is defined as random and independent of x_i. With these assumptions Newhouse et al (1982) have shown that the averaged mean square of the Lattice Transfer Function which we define as Characteristic Lattice Spectrum is given by

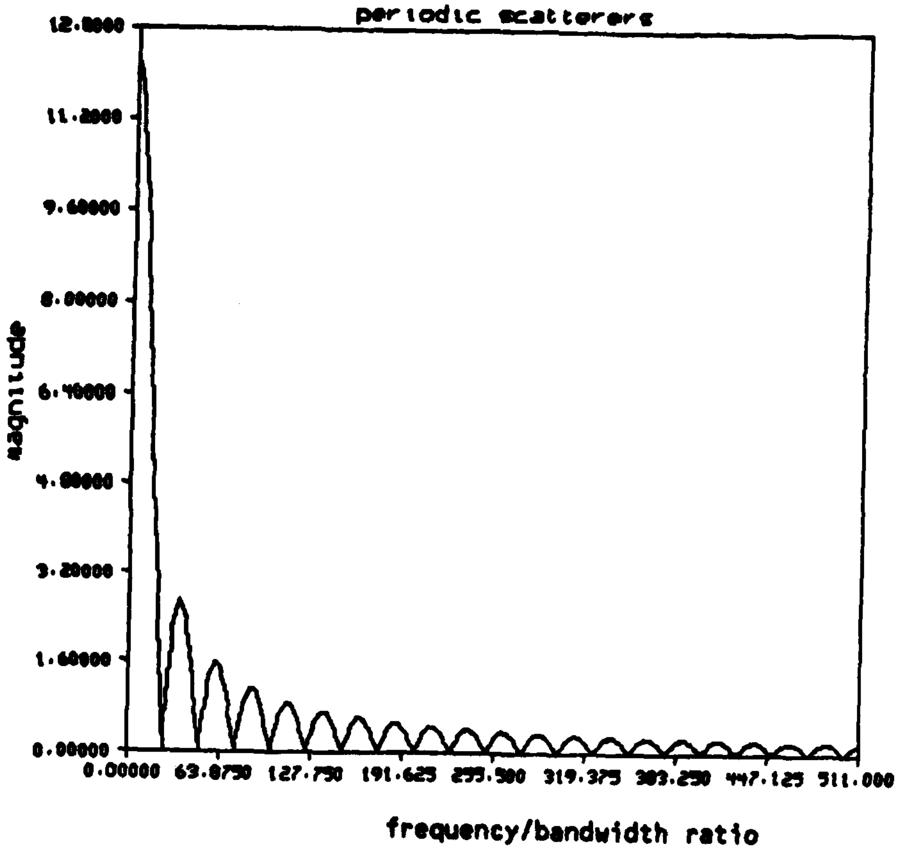


Fig. 2. Calculated Characteristic Lattice Spectrum for periodic lattice (eq. 3). N = 50, B = 25, a = 3.

$$<|M(f)|^2 = M_s(f) = N <a^2> + N^2 <a>^2 \operatorname{sinc}^2\left[\frac{\pi f}{B}\right] \tag{4}$$

if $N >> 1$.

Thus N is again the number of scatterers in the range cell. The terms $<a>$ and $<a^2>$ are respectively mean amplitude and mean square amplitude of the scatterers, and $<>$ stands for the ensemble average.

Figure 3 shows the characteristic spectrum of an aperiodic lattice given by eq. (4). As in the case of the periodic lattice shown in Figure 2, it is seen to have minima at the destructive interference frequencies $f\,\tilde{=}\,B$, 2B, 3B etc. In contrast to the earlier spectrum however, the aperiodic lattice spectrum is seen to approach the limit $N<a^2>$ at $f\,\tilde{=}\,\infty$. This feature can be interpreted in terms of Rayleigh's theorem which states that the time averaged energy back-scattered from N incoherently moving scatterers separated by distances large compared to the incident wavelength is proportional to the sum of the energy reflected by each scatterer. In averaging the spectra M(f) of stationary aperiodic scatterers we have ensemble averaged the sum of echo energies which is equivalent to time averaging time samples of energy back-scattered from incoherently moving scatterers. Hence our calculated average echo spectral density $M_s(f)$ (given in eq. (4)) which is proportional to the average power back-scattered from many ensembles, equals the product of N the number of scatterers per ensemble, multiplied by $<a^2>$ the average scatterer cross-section, at high frequencies.

QUASI-PERIODIC LATTICE

The type of lattice considered above, in which the scatterer ranges are uniformly distributed, is mathematically simple but probably less realistic than the case of a Lattice Impulse Response in which the *intervals* between successive scatterer are uniformly distributed around an average value. This case corresponds closely to the Lattice Impulse Response functions obtained for beams oriented along directions of lattice symmetry in periodic lattices, as illustrated in Figure 1a. It therefore probably provides a better model for quasi-periodic lattices than does the type of lattice analyzed above.

Since the grain scattering cross section is probably proportional to its volume, we will assume a Lattice Impulse Response in which the amplitude a_i of the ith scatterer is related linearly to its spacing d_i from the i-1th scatterer, i.e. $a_i = k\, d_i$ where k is a constant. Under these assumptions a somewhat lengthy calculation shows that the Characteristic Lattice Spectrum for the quasi-periodic lattice is

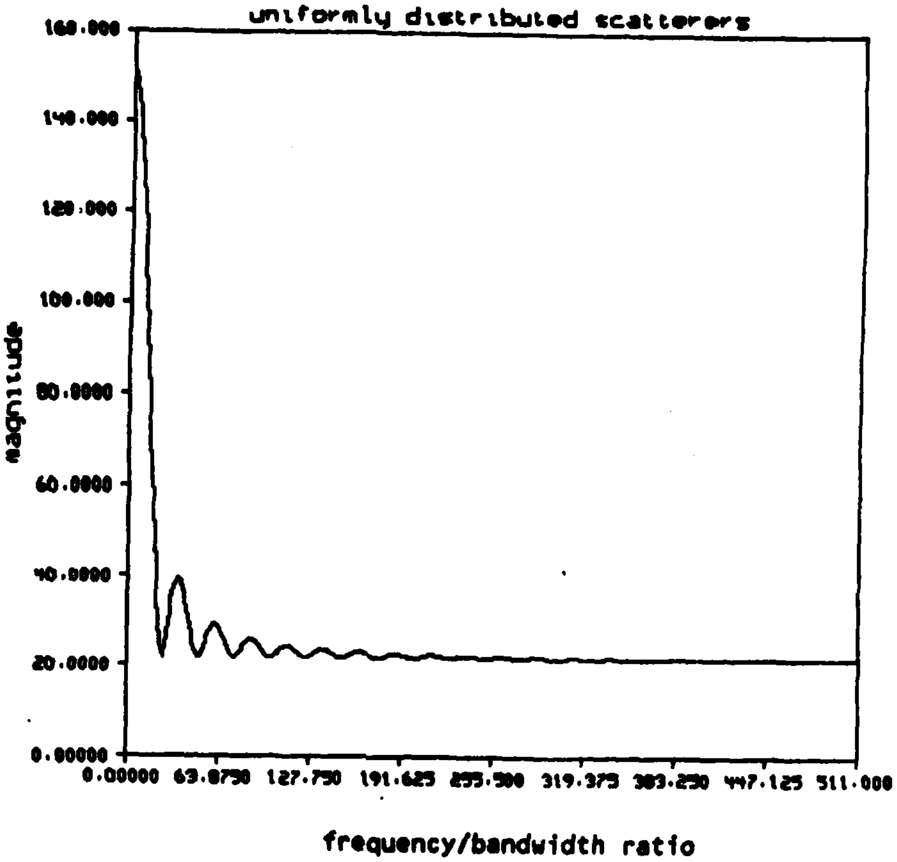


Fig. 3. Calculated Characteristic Lattice Spectrum for aperiodic lattice (eq. 4). N = 50, B = 25, $\langle a \rangle = 3$, $\langle a^2 \rangle = 9.33$.

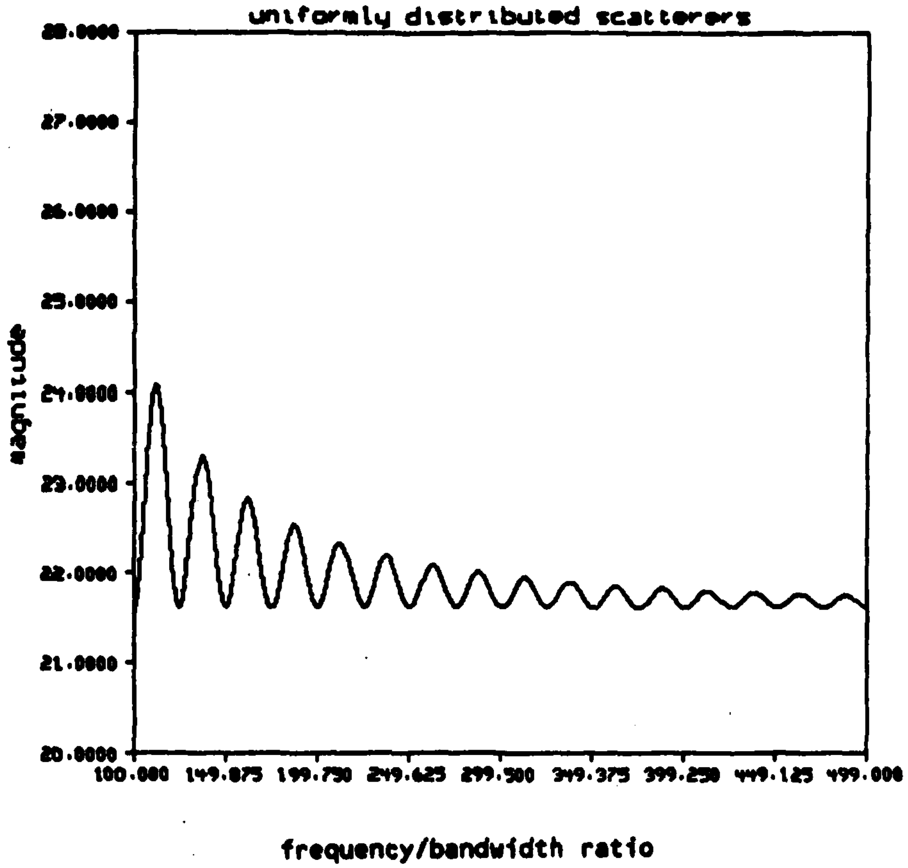


Fig. 4. A portion of Fig. 3 plotted to a different scale.

$$M_s(f) = <|M(f)|^2> = N<a^2> + <a>^2 \sum_{i=1}^{N} \sum_{\substack{j=1 \\ i=j}}^{N} e^{-\sigma_i^2/2-\sigma_j^2/2} \cos[m_i - m_j] \qquad (5)$$

where $m_i = i\,(\frac{2\pi f}{c})<d>$ for $i = 1,2,\ldots,N$

and $\sigma_i^2 = i\,(\frac{2\pi f}{c})^2\,[<d^2> - <d>^2]$ for $i = 1,2,\ldots,N$

The magnitude of the Characteristic Lattice Spectrum for the quasi-periodic lattice given in eq. (5) is plotted in Figure 5. This reveals the same minima caused by interference as we saw in the spectra of the two lattices analyzed above. It also shows the same asymptotic approach to the Rayleigh value $N<a^2>$ at high frequencies as found in the spectrum of the aperiodic lattice.

We believe that our model of a quasi-periodic lattice whose Characteristic Lattice Spectrum is shown in Figure 5 will prove to be a useful model for real grains. We use this model below, first to simulate grain echoes and then to demonstrate our techniques for extracting the Characteristic Lattice Spectrum from these echoes.

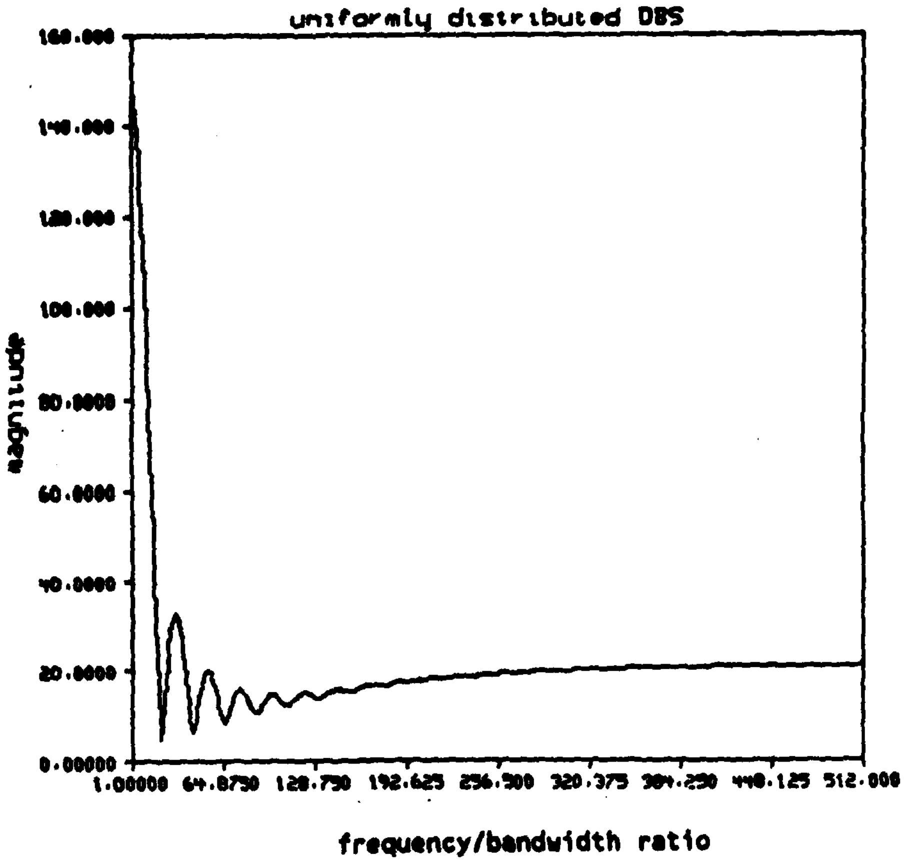


Fig. 5. Calculated Characteristic Lattice Spectrum of quasi-periodic lattice (eq. 5). Parameters as in Fig. 4.

SIMULATION OF LATTICE SPECTRUM AND ECHOES

SIMULATION OF CHARACTERISTIC GRAIN SPECTRUM

To simulate the lattice spectrum we start by using a random number generator to generate a number LN of scatterer amplitudes a_i and intervals d_i using a specified mean value and variance. The intervals d_i are then used to compute the scatterer echo delay τ_i by using the relation

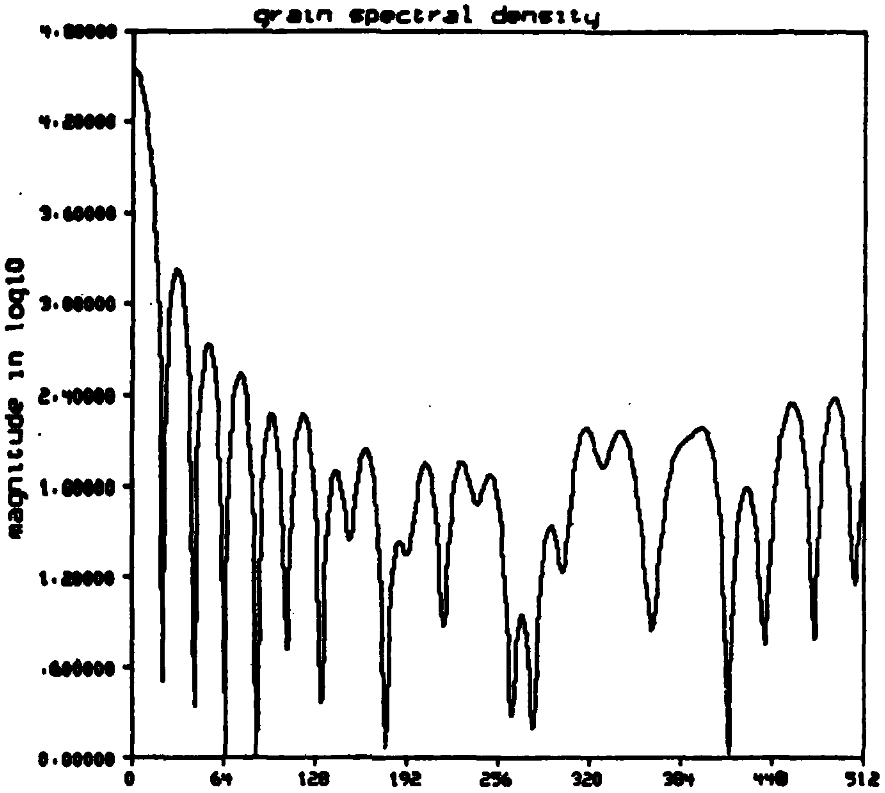
$$\tau_i = \sum_{j=1}^{i} \frac{2d_j}{c}, \quad \text{for } i = 1,2,3,\ldots,N$$

Finally we calculate the Lattice Impulse Response for a lattice region containing LN scatterers, using the relation

$$m(t) = \sum_{i=1}^{LN} a_i \, \delta(t-\tau_i) \tag{6}$$

To obtain a sample function M(f) of the Lattice Transfer Function we Fourier transform eq. (6). The magnitude of a typical example of such a Lattice Transfer Function is plotted in Figure 6.

To calculate the Characteristic Lattice Spectrum of the simulated Lattice Impulse Response we must average the sample function M(f) in some way. Our procedure has been to split the calculated Lattice Impulse Response sample function m(t) given by eq. (6) into L equal length segments which are then Fourier transformed. Finally these L Fourier transforms are averaged to produce the Characteristic Lattice Spectrum of our simulated Lattice Impulse Response. The magnitude of such a simulated Characteristic Lattice Spectrum is plotted in Figure 7 and is seen to agree closely with the *calculated* Characteristic Lattice Spectrum which was given in Figure 5 and which is shown replotted in Figure 12. The agreement although not perfect is good enough to demonstrate that the calculated relation (eq. (5)) for the Characteristic Lattice Spectrum is correct or nearly correct, and that such a function can actually be



frequency/bandwidth ratio

Fig. 6. Simulated sample function of lattice echo spectrum $|M(f)|^2$. LN = 500, L = 10, B = 25, $\langle a \rangle = 3$, $\langle a^2 \rangle = 9.33$.

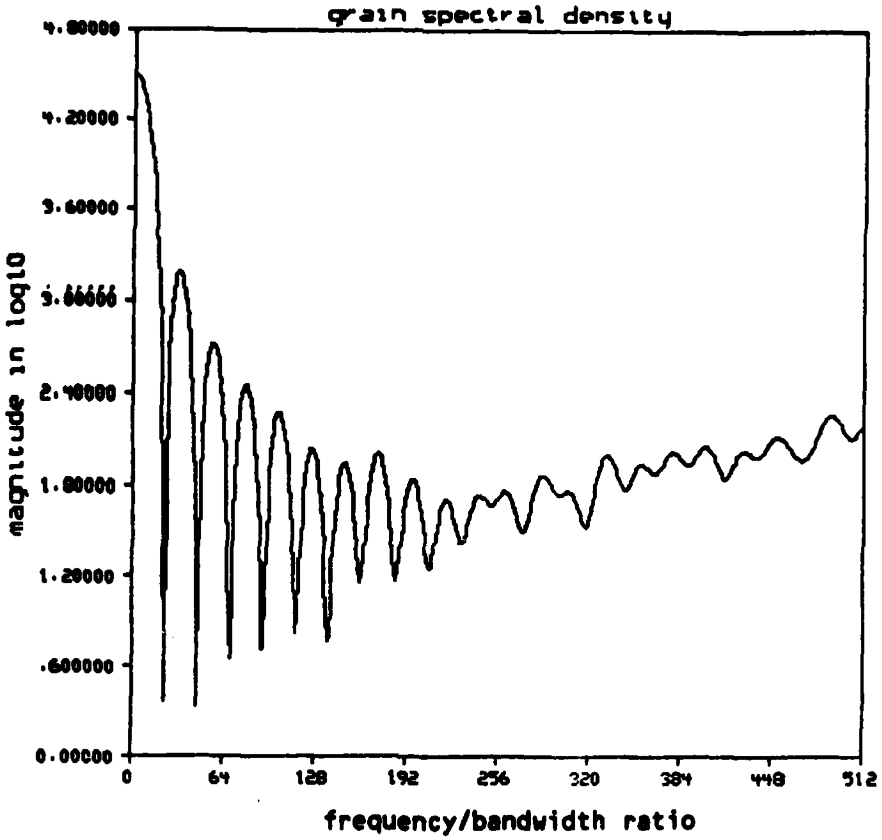


Fig. 7. Characteristic Lattice Spectrum calculated by averaging 10 sections of simulated echo spectrum $|M(f)|^2$. Parameters as in Fig. 6.

extracted by suitably averaging sample functions of the Lattice Transfer Function.

SIMULATION OF THE ECHO SPECTRUM

The output of the type of correlation receiver we are using for this research is usually displayed as a function of echo time of flight. For an infinitely thin flat planar reflector at a range corresponding to an echo delay time τ_0 we will write the receiver output as $r(\tau-\tau_0)$. The function $r(\tau)$ is the autocorrelation function of the transmitted signal after it has passed through the sending and receiving transducer. If this signal has a Gaussian shaped spectrum of bandwidth B and center frequency f_0, then the autocorrelation function (which has been used in this work) is

$$r(\tau) = e^{-\pi^2 B\tau} \cos 2\pi f_0 \tau \tag{7}$$

When viewing an ensemble of scatterers with Lattice Impulse Response $m(\tau)$ (see eq. (1)), the correlation receiver output will be

$$e(\tau) = r(\tau) * m(\tau) \tag{8}$$

A computed echo sample function of this type corresponding to a length of beam intercepting 500 scatterers is shown in Figure 8, and the corresponding spectrum is shown in Figure 9.

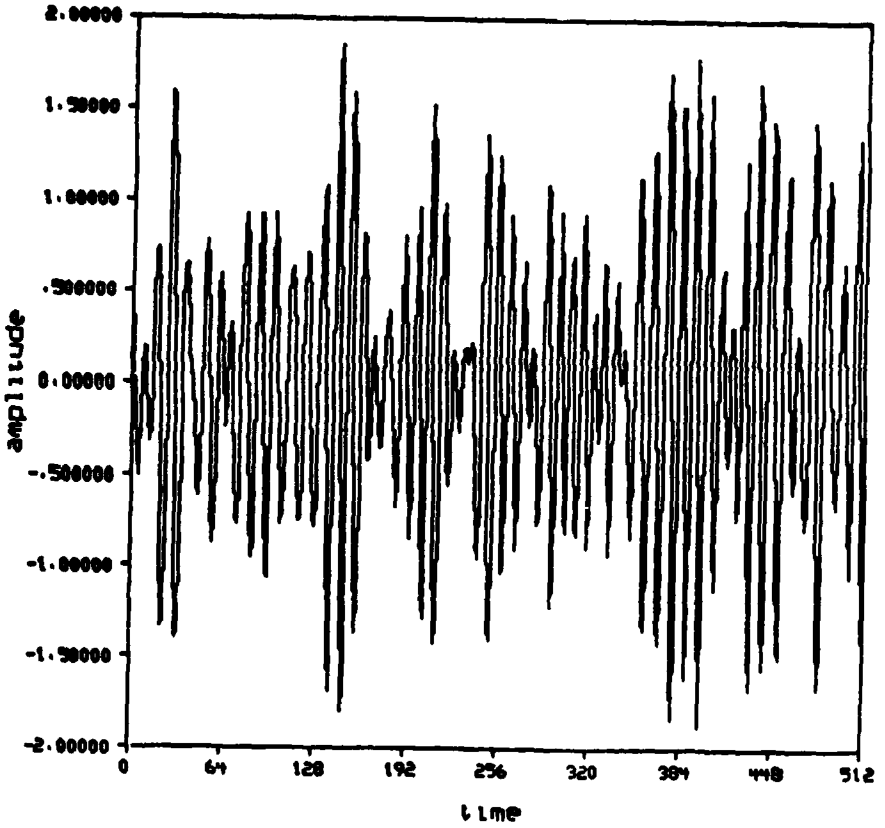


Fig. 8. Simulation of grain echoes after processing by correlation receiver (eqts. (1) and (7)). $f_0 = 400$, $B = 200$, $N = 500$, $L = 10$, $\langle a \rangle = 3$, $\langle a^2 \rangle = 9.33$.

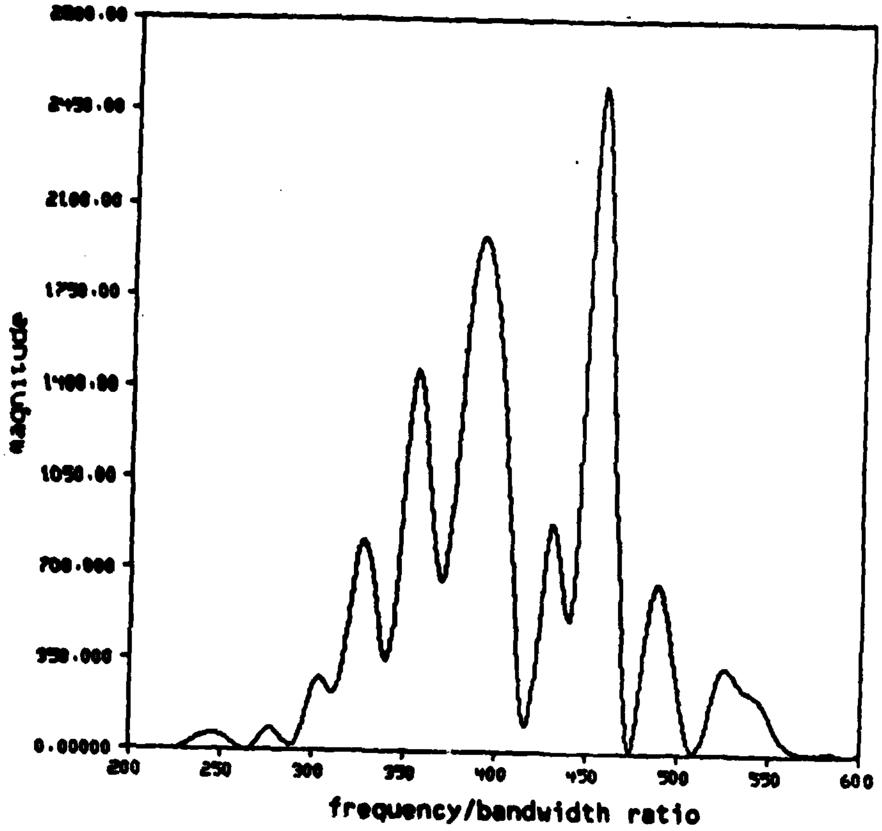


Fig. 9. Simulated spectrum corresponding to signal of Fig. 8.

DECONVOLUTION OF THE CHARACTERISTIC SPECTRUM

To extract the Characteristic Lattice Spectrum from the echo we must first calculate a "Characteristic Echo Spectrum", which is analogous to the Characteristic Lattice Spectrum. An analogous procedure to that used for the Characteristic Lattice Spectrum is employed. First the echo function e(τ) given in (8) is split into 10 equal segments which are then Fourier transformed. The magnitude of one of these transforms, corresponding to a sample function of the echo spectrum of 50 scatterers, is plotted in Figure 9. When 10 of these transforms are averaged, we obtain the "Characteristic Echo Spectrum" whose magnitude is plotted in Figure 10. Figures 8 through 10 show that by suitable processing it is possible to extract a characteristic average spectrum from the grain echo.

To discover how to derive the Characteristic Lattice Spectrum from the Characteristic Echo Spectrum Fourier we transform eq. (7) to obtain

$$E(f) = S(f)\, M(f) \qquad (9)$$

where E(f) and M(f) are sample functions of the Fourier transforms of the echo of the Lattice Impulse Response, and where S(f) ***is the Fourier transform of r(τ)*** **which is known to be the spectrum of the correlation system echo signal when observing a plane reflector.**

Squaring and ensemble averaging gives the Characteristic Echo Spectrum

$$<|E(f)|^2> = S^2(f) <|M(f)|^2>$$

showing that the Characteristic Lattice Spectrum can be obtained by deconvolving the Characteristic Echo Spectrum with respect to S(f). In the present simulation, where these is no noise signal, this deconvolution process can be performed by simple division, i.e.

$$M_s(f) = <|M(f))^2> = \frac{<|E(f)|^2>}{S^2(f)}$$

The result of deconvolving the Characteristic Echo Spectrum of Figure 10 with the assumed correlation system spectrum by simple division is shown in Figure 11. Comparison of Figure 11 with Figure 12 shows that the Characteristic Lattice Spectrum obtained from the simulated echo signal agrees closely with the Characteristic Lattice Spectrum calculated for a Lattice Impulse Response having the statistics of the lattice used for the simulation. Since we know how the calculated Characteristic Lattice Spectrum depends on grain statistics, we may confidently expect to be able to extract

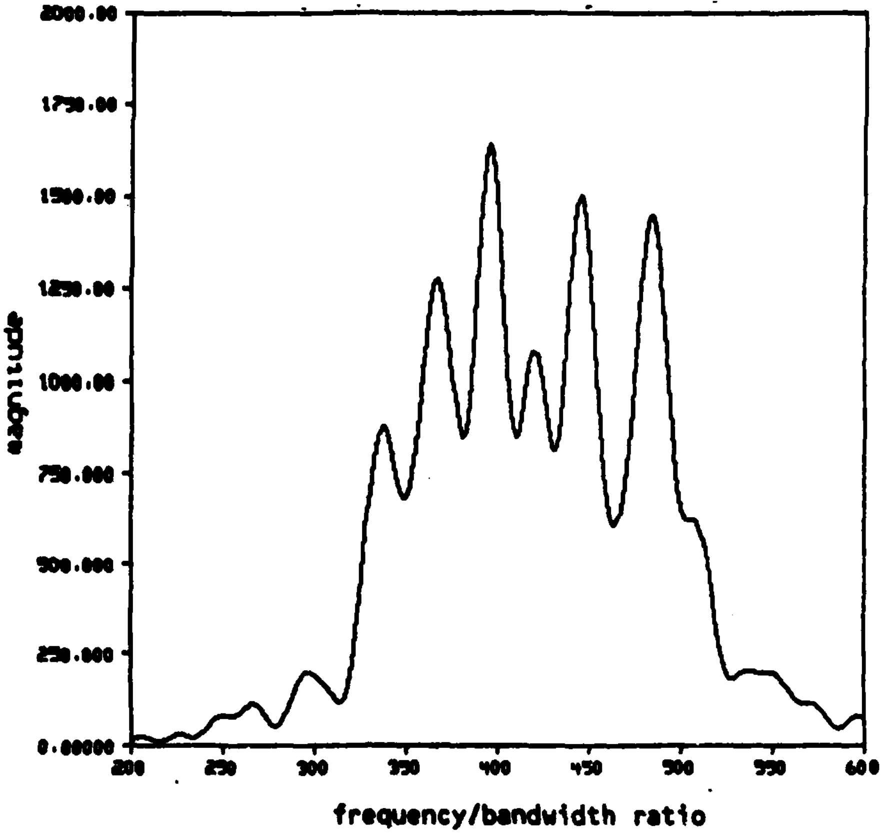


Fig. 10. Average of 10 portions of spectrum whose magnitude is shown in Fig. 9.

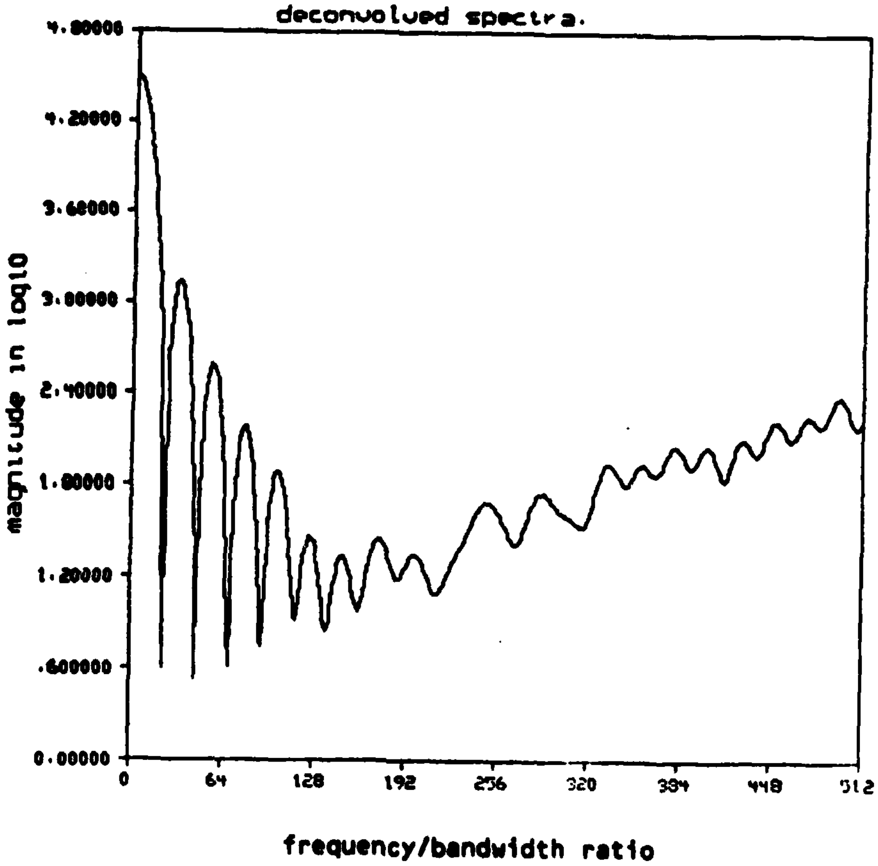


Fig. 11. Characteristic Lattice Spectrum produced by deconvolving simulated spectrum of Fig. 10 with correlation system spectrum.

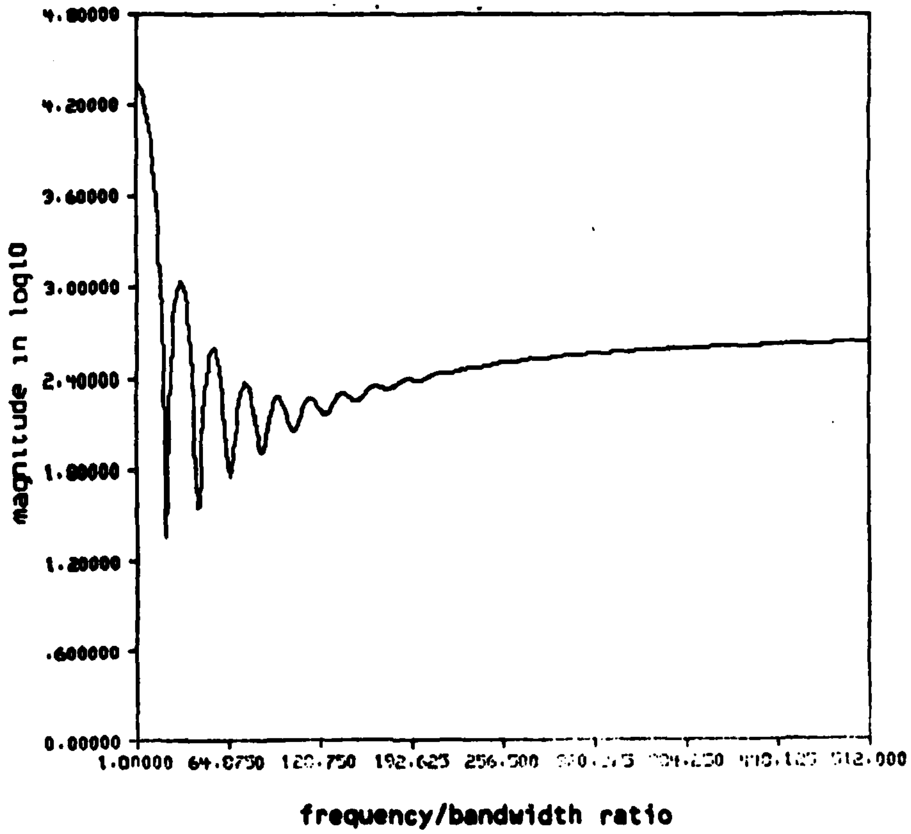


Fig. 12. Calculation of the Characteristic Lattice Spectrum of Fig. 11, using eq. (5), (see also Fig. 5).

these statistical parameters from an experimentally obtained Characteristic Lattice Spectrum.

SUMMARY OF RESEARCH ACTIVITY

The principal activities of the first seven months of this program were previously detailed in a continuation request for this project prepared in January 1982. The theoretical calculations and computer simulations carried out at Purdue during that period appear in this final project report.

The activities comprising the Drexel University subcontract during the remainder of the first year of this program are described by Prof. Newhouse in an appendix of this report.

During the early part of calendar year 1982, the effort at Purdue concentrated on developing a suitable sample set for evaluation of the signal processing algorithms being developed under subcontract to Drexel University. To be suitable for verification of the existing theoretical calculations, the targets used to simulate grain echo signals were required to have a relatively sparse distribution of reflectors and very low ultrasonic attenuation. After examining a wide variety of possible materials, it was decided that urethane foam satisfactorily met these requirements provided that all the gas inclusions were displaced by water.

The use of urethane foam for the initial simulations of grain back-scattered ultrasonic signals permitted some control of the scatterer spacing and reflecting power of the scatterers through the selection of suitable grades of commercially available foam. Several samples were prepared and characterized in preparation for testing the microstructure parameter extraction algorithms. At this point, we were informed by the Drexel group that some delay was anticipated in delivering signal processing algorithms suitable for use with experimental data. Consequently, those activities related to experimental verification of the proposed microstructure parameter extraction procedures were suspended, awaiting delivery of the signal processing algorithms.

In the interim, the Purdue group began to explore the statistics that would actually be expected for the back-scattered ultrasonic signal from a small grain metal sample. Grain size distributions for materials in which the grains can be characterized by a single dimension (i.e. not elongated) are known to be reasonably well approximated by the log-normal distribution function. This result has previously been established by other researches through measurements on optical micrographs of a variety of materials.

For any known (or assumed) three-dimensional distribution of grains, it is possible to calculate the exact back-scattered ultrasonic signal that is expected by summing the echoes from the individual scatterers illuminated by the ultrasound, and by taking the frequency dependence of the scattering from the individual reflectors into account along with the frequency characteristics of the ultrasonic transducer. For any such back-scattered signal there exist relatively sparse one-dimensional arrays of scatterers which would reproduce this received signal to any desired degree of accuracy. Although the mathematical formalism for determining suitable statistics for the equivalent one-dimensional scatterer arrays is relatively straightforward, the link between the original three-dimensional statistics and equivalent one-dimensional scatterer array seems very weak.

This observation led us to an investigation of methods required to recover the actual microstructure parameters assuming for the present that the algorithms being developed at Drexel could accurately extract the statistics of the equivalent one-dimensional scatterer array. This effort raised some concern that the process whereby the three-dimensional statistics were collapsed to one-dimension could not be successfully inverted. Unfortunately, since we were notified by Drexel that continuation of this effort would not be supported, this investigation was terminated before resolution of this question.

In hopes of completing our portion of the effort proposed for the first year, we asked for an extension of the period of performance to allow experimental evaluation of the signal processing algorithms being developed at Drexel following the completion of the Drexel subcontract. However, since no signal processing algorithms or other technical results were produced and transmitted to Purdue as a result of the Drexel subcontract, experimental verification of the proposed technique for microstructure evaluation was not carried out.

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APPENDICES

DREXEL UNIVERSITY REPORT

Final Report for Period Jan. 1- June 30, 1982
by V. L. Newhouse Ph. D.

The work performed at Drexel University during this period can be divided into three categories.

1. THEORETICAL

a. Attenuation

In the theory developed up to December 1981, attenuation of ultrano~~rmal~~sound echoes due to absorption and scattering had not been taken into account. During the current reporting period this omission has been rectified and incorporated into our calculated expression for the characteristic lattice spectrum. This work has shown that the maximum ~~length of~~ signal length (the so-called time window) used for ~~air~~ processing, must not be long enough for attenuation to become appreciable.

b. Accuracy of Spectrum Estimate

Since our method of grain size estimation should operate even for grains much smaller than the illuminating wavelength, it is important to calculate the accuracy of our estimates so as to be able to deduce the lower size limit of the grains which can be measured. During the current reporting period we have shown theoretically-neglecting quantum effects- that to first order, the percentage uncetainty of our estimates of both grain size and accoustic scattering cross-section, should be independent of the magnitude of these quantities, and can be made arbitrarily small by increasing the number of measurements, or the measurement time. This is somewhat similar to estimating the average radius of a quantity of ballbearings of known density by first weighing them and then measuring their total volume. In that case, the accuracy of the estimated radius depends only on the uncertainty of the weighing and volume measuring process and the number of estimates, rather than on the radius magnitude.

2. SIGNAL PROCESSING

a. Parameter Estimation

The evaluation of the grain size and scattering cross-section parameters is done by comparing a measured characteristic spectrum to a calculated spectrum and adjusting the parameters to be estimated for the best fit. A number of mathematical procedures exist for this process of parameter estimation, with the choice of the optimum procedure depending on the function being considered. During the current reporting period we have examined the properties of calculated characteristics spectra for two types of lattice with respect to parameter estimation and shown that the characteristic lattice function for uniformly distributed scatterers can be used to estimate two lattice parameters, whereas the spectrum for the quasi-periodic lattice will serve to estimate four parameters.

Several known parameter estimation techniques have been compared on simulated data.

b. Deconvolution

One of the steps of our lattice parameter estimation procedure involves deconvolving the averaged echo spectrum with respect to the transducer response. Several different known deconvolution techniques have been reviewed, and our currently used simulated deconvolution procedure is being made more realistic.

3. EXPERIMENTAL

In estimating grain sizes from grain echoes it is important to have a very good signal to noise ratio for the aquired echoes. We have set up a microprocessor controlled random ~~regional~~ signal correlation system for data aquisition which is now fully functional and ready to aquire grain echo data with excellent signal to noise ratio.

4. PUBLICATIONS

We have presented a paper at the recent NBS Tissue Characterization and Ultrasonic Imaging Conference and are planning presentation at the DARPA/AFML Conference in San Diego. We have been invited to present the work at the IEEE Bioengineering Conference in October 1982. The strong bioengineering interest in this technique is due to the fact that as well as estimating grain size, it will probably also be important in characterizing different types of tissue.

Sincerely,

Vernon L. Newhouse, Ph. D.
Disque Chair Professor
Electrical and Computer Engineering

VLN/tl

LIST OF PUBLICATIONS AND CONFERENCE PRESENTATIONS
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