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CEPSTRAL METHOD FOR THE MEASUREMENT OF ULTRASONIC PULSE TRANSMISSION TIME VARIATIONS

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MATERIALS TESTING AND EVALUATION BRANCH

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ABSTRACT

A precise method for determining relative changes or small differences in ultrasonic pulse transmission times has been developed. The method uses multiple-echo signals obtained by injecting a pulsed, plane ultrasonic wave of the compressional mode into a sample with free, parallel surfaces. The ultrasonic transducer employed for this purpose acts as both transmitter and receiver. The received ultrasonic signals are subjected to two consecutive Fourier transformations to produce a cepstrum. The cepstral function derived from the multiple-echo signal exhibits characteristic maxima whose positions on the quefrency abscissa, after calibration in units of time, represent multiples of the ultrasonic transmission time. Since minute variations of this time can be determined from a shift in the position of a cepstral maximum, the detection of very small changes or differences in sample thickness or ultrasonic propagation velocity becomes feasible.

Keywords: → to field 19

INTRODUCTION

In ultrasonic pulse-echo testing, a pulsed signal is injected into the test specimen at an accessible surface by a transducer which usually also functions as a receiver to pick up echo returns from internal discontinuities or reflecting surfaces. If the specimen has a back surface which is essentially parallel to the entrance surface, the injected ultrasonic pulse will reverberate between the two surfaces and give rise to multiple-echo signals. The time intervals between these echoes represents the duration of a round trip of the ultrasonic pulse through the sample, or twice its transmission time. If the ultrasonic velocity in the tested material is known, the sample thickness can be derived from this transmission time. On the other hand, if the dimensions of the sample can be determined by other means, a measurement of the transmission time will yield the ultrasonic propagation velocity. The precision of such thickness or velocity measurements depends on how accurately the time intervals between multiple-echo indications can be determined.[*] [1,2] For materials with low ultrasonic attenuation as, for example, aluminum or fused quartz, the amplitudes of consecutive-echo indications decay only moderately and the intervals between them are therefore usually well defined. But materials that have high ultrasonic attenuation produce multiple echoes whose amplitudes decay rapidly and exhibit changes in pulse shape. As a result, the contours of these echo indications lack comparable featured that are suitable as reference points to accurately determine the beginning and the end of the time interval between a pair of consecutive echoes.[3]

In order to overcome this problem and be able to ultrasonically examine highly attenuating materials such as composites, a cross-correlation method has been proposed by Hull, Klutz, and Vary.[3] In this report, a different approach will be discussed which is based on producing a cepstrum of the multiple-echo indications received from a test sample.

BASIC CONCEPT OF CEPSTRAL METHOD

The method of measuring ultrasonic transmission times to be discussed involves two consecutive Fourier transformations of the ultrasonic multiple-echo signal received from a test sample. First, a magnitude spectrum is obtained which exhibits characteristic amplitude fluctuations consisting of maxima and minima that follow upon each other at frequency increments representing the reciprocal of the intervals between ultrasonic echo indications in the time domain. Thickness measurements based on an analysis of spectral functions have been reported by Rose and Meyer[4] and by Paradis, Serruys, and Saglio.[5] The method presented in this report goes one step further and subjects the magnitude spectrum of the multiple-echo signal to another Fourier transformation to obtain a function which usually is

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[*] GERICKE, O.R. *Method for Precision Ultrasonic Thickness or Velocity Measurement.* U.S. Army Materials Technology Laboratory, Watertown, MA, Disclosure of Invention, June 1986.

1. BOSSELAR, H., and GOOSSENS, J. C. J. *Method to Evaluate Direct-Reading Ultrasonic Pulse-Echo Thickness Meters.* Materials Evaluation, v. 19, no. 3, 1971, p. 45.
2. KAULE, W., WETZLAR, K. E., and OWENS, W. T. *A New Method of Ultrasonic Wall Thickness Measurement: The Predef System.* Materials Evaluation, v. 32, no. 5, 1974, p. 103.
3. HULL, D. R., KAUTZ, H. E., and VARY, A. *Measurement of Ultrasonic Velocity Using Phase-Slope and Cross-Correlation Methods.* Materials Evaluation, v. 43, no. 11, 1985, p. 1455.
4. ROSE, J. L., and MEYER, P. A. *Ultrasonic Signal Processing Concepts for Measuring the Thickness of Thin Layers.* Materials Evaluation, v. 32, no. 12, 1974, p. 249.
5. PARADIS, L., SERRUYS, Y., and SAGLIO, R. *Ultrasonic Signal Processing for Thickness Measurements and Detection of Near-Surface Defects.* Materials Evaluation, v. 44, no. 11, 1986, p. 1344.

referred to as a cepstrum.[6-8] The term cepstrum and associated terminology is explained in detail in the article by Randall and Hee.[8]

The cepstral function is plotted on a so-called quefrency abscissa[8] which can be calibrated in units of time to represent the reciprocal of the frequency scale of the underlying spectrum. If this is done, the cepstral function will give an account of the combined effect of all multiple-echo intervals in the original ultrasonic signal. The Fourier transformation can be carried out in such a way that the origin of the cepstrum becomes time zero in which case an initial, zero order cepstral maximum will be observed. Depending on the selected time scale of the Fourier transformation, the zero order cepstral maximum will be followed by one or more higher order maxima if the underlying spectrum exhibits amplitude fluctuations that are due to a periodicity of the ultrasonic indications in the time domain.

If the quefrency scale is appropriately chosen, the cepstral maximum of first order observed right after the zero order maximum occurs at a time corresponding to the average time interval between multiple-echo indications which is equal to twice the transmission time through the test specimen. Higher order cepstral maxima appear at multiples of this time with multiplication factors equivalent to the order number of the maximum. Thus, to get the duration of the multiple-echo interval from a selected cepstral maximum, the time of the maximum's position on the quefrency scale has to be divided by its order number. A subsequent division by two, finally, will yield the ultrasonic transmission time through the test specimen.

To illustrate the above outlined process, Figures 1 through 3 show the time-, frequency-, and cepstral-domain functions obtained from a 0.5-inch-thick polycrystalline aluminum plate with free parallel surfaces after injection of a pulsed ultrasonic signal of the longitudinal wave mode having a plane wave front. The ultrasonic transducer used for this purpose consists of a piezoelectric element resonant at about 2.25 MHz to which a damping body is attached to attain a broad frequency response of about 1 to 4 MHz. Only the first five multiple-echo indications received due to the repeated round trips of the injected ultrasonic signal through the aluminum plate are selected for further processing. They are displayed in Figure 1.

Figure 2 shows the magnitude spectrum of the pulse-echo train of Figure 1 obtained by means of a fast Fourier transform (FFT). The envelope of this line spectrum represents the frequency response characteristic of the employed ultrasonic transducer.[9] The frequency increment from one spectral line (or maximum) to the next is about 0.25 MHz or the reciprocal of the approximately 4.0 microseconds multiple-echo interval in Figure 1.

Figure 3 depicts the cepstrum derived from the spectrum of Figure 2 by an FFT yielding a zero, first, and second order cepstral maximum on a quefrency abscissa calibrated to represent a time range of 0 to 10.24 microseconds. The time position of the cepstral maximum of first order is about 4.0 microseconds which is equivalent to the multiple-echo interval in the time domain (Figure 1).

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[6] BOGART, B. P., HEALY, M. J. R., and TUKEY, J. W. *The Quefrency Analysis of Time Series for Echoes, Cepstrum, Pseudo-Autocovariance, Cross Cepstrum and Saphe Cracking.* Chapter 15 in Time Series Analysis, M. Rosenblatt, ed., John Wiley and Sons, New York, 1963, p. 209.

[7] KANASEWICH, E. R. *Cepstrum and Quefrency Analysis for Echoes.* Chapter 20.1 in Time Sequence Analysis in Geophysics, The University of Alberta Press, 1981.

[8] RANDALL, R. B., and HEE, J. *Cepstrum Analysis.* Wireless World, February 1982, p. 77.

[9] GERICKE O. R. *Experimental Determination of Ultrasonic Transducer Frequency Response.* Materials Evaluation, v. 24, no. 8, 1966, p. 409.

Figure 3 indicates 8.0 microseconds to be the time position of the second order cepstral maximum. Dividing this value by two, the order number of maximum, again yields 4.0 microseconds. A further division by two leads to 2.0 microseconds as the ultrasonic transmission time through the 0.5-inch-thick sample from which the ultrasonic velocity in the tested aluminum material is derived as 2.5 10^5 inches or 6.3 10^3 meters per second.

ACCURACY OF CEPSTRAL METHOD

The accuracy of ultrasonic pulse transit time measurements conducted on the basis of the cepstral method depends on several factors. The first is the number of data points acquired in the time domain by the process digitizing the received ultrasonic signal. The second factor is the data point resolution delivered by the Fourier transformation procedures employed to generate the spectral and cepstral functions.

In the example portrayed by Figures 1 through 3, the digitized time-domain function (Figure 1) consists of 2048 points spanning a time range of 3 to 23.48 microseconds. Thus, data points are spaced 10 nanoseconds apart. The magnitude spectrum obtained from this time function by an FFT procedure has 128 data points extending over a frequency range of 6.25 MHz which covers the frequency response band of the ultrasonic transducer used for the test. These spectral data points are shown individually in Figure 4.

The cepstrum of Figure 3 consists of 512 data points covering a time range of 10.24 microseconds. The cepstral time resolution, therefore, is 10.24/512 microseconds or 20 nanoseconds. Since the measurement of the ultrasonic transmission time based on a cepstral maximum of first order involves a division by two, the measurement error becomes ± 10 nanoseconds. If the ultrasonic transmission time is determined from the second order cepstral maximum, the ensuing division by four results in an error of ± 5 nanoseconds. Thus, the higher the order number of the cepstral maximum on which the measurement is based, the better the accuracy of the method.

The measurement error can be reduced to one half of the above values if a digitizing process is chosen for the acquisition of the multiple-echo train of Figure 1 which produces 4096 rather than 2048 data points. In that case, a cepstrum is obtained that has 1024 data points spaced only 10 nanoseconds apart. Thus, a measurement based on the cepstral maximum of second order will now have an error of only ± 2.5 nanoseconds.

Another important factor governing the accuracy of the cepstral method is the type of Fourier transformation technique chosen for processing the ultrasonic time function, as well as its spectrum. A significant improvement can be achieved if a transformation technique called a Chirp Z Transform (CZT)[10] is substituted for the FFT as discussed next.

ACCURACY IMPROVEMENT OBTAINED WITH A CHIRP Z TRANSFORM

The accuracy of the cepstral method can be greatly enhanced through the use of a recently implemented CZT algorithm.[11] Its primary advantage is to offer greater flexibility for the selection of transformation ranges than does an FFT algorithm. As a result, improvements in resolution are attainable in both the spectral and the cepstral domain.

[10] OPPENHEIM, A. V., and SCHAFER, R. W. *Digital Signal Processing.* Prentice-Hall, Englewood Cliffs, NJ, 1975, p. 321.

[11] CURRAN, L. *Fast Fourier Transform Meets its Match in Chirp Z.* Electronics, October 1, 1987, p. 33.

As shown by Figure 4, an FFT of the pulse train of Figure 1 yields only 128 data points for the frequency range of 6.25 MHz. In contrast, a CZT will produce 512 data points for the same frequency range as is illustrated in Figure 5.

This constitutes a four-times improvement in resolution which greatly benefits the signal-to-noise ratio of the cepstral trace derived from the spectrum. This is illustrated by Figure 6, obtained through a CZT of the spectrum of Figure 5 which, in comparison to Figure 3, shows a much smoother curve.

In generating the cepstrum, the use of a CZT instead of an FFT offers an important additional advantage. It permits spreading the display of a specific cepstral maximum over all 512 data values of the transformation function. This feature of the CZT can be utilized to significantly enhance the time resolution of the cepstral method. As an example, Figure 7 depicts the expanded trace of the cepstral maximum of second order seen in Figure 6. To effect this expansion, the time range of the CZT is reduced eight times to 1.28 microseconds. Thus, the 512 data values are now spaced only 1.28/512 microseconds or 2.5 nanoseconds apart. As a result, since the time position of the cepstral maximum of second order represents the ultrasonic pulse transmission time multiplied by a factor of four, the resolution for determining this transmission time now becomes 2.5/4 nanoseconds or 625 picoseconds.

The resolution can be further improved to a value of 2.5/10 nanoseconds or 250 picoseconds if the measurement is based on the cepstral maximum of order five rather than two. Figure 8, which shows the expanded cepstral maximum of fifth order, indicates, however, that its trace has a much higher noise level than the second order maximum shown in Figure 7. Noise fluctuations can lead to a large error if an electronic peak reading technique is used to find the time position of this maximum. The problem is alleviated by filtering the cepstral signal to remove fluctuations prior to the electronic analysis. The beneficial effect on the signal-to-noise ratio obtained through the filtering action of a signal convolution is illustrated by Figure 9, which should be viewed in comparison with Figure 8.

The possibility of improving the resolution of the cepstral method by analyzing maxima of high order is a considerable advantage of the CZT versus the FFT algorithm. That approach is limited, however, because an increase in the order number of the cepstral maximum is accompanied by a rise in the noise level which ultimately becomes unmanageable.

APPLICATION OF THE CEPSTRAL METHOD TO A COMPOSITE MATERIAL

As mentioned at the beginning, materials that, due to their elastic properties and/or microstructure exhibit high ultrasonic attenuation, pose a problem for ultrasonic thickness or velocity measurements. The sharp decline in amplitude from one multiple echo to the next accompanied by a distortion of the pulse shape makes a precise determination of the time intervals between these echoes impossible.

This problem is illustrated in Figure 10 which shows a multiple-echo train obtained from an 0.5-inch-thick plate made of a graphite/epoxy composite material with high ultrasonic attenuation. The significant drop off in amplitude from one echo to the next is associated with changes in pulse shape which are more easily demonstrated if the traces of the first and second back-surface echo are superimposed.

Figure 11 depicts such a superposition. To render the differences in pulse shape more distinguishable, the amplitude of the second echo has been increased six times relative to that of the first echo. Figure 11, which represents the so called overlap method,[3] makes it obvious that an accurate measurement of the time interval between the two echoes is not feasible because the two traces lack comparable features that could serve as reference points. This problem, which exists regardless of whether the evaluation is done by direct observation of the traces or by means of an analog or digital electronic analysis,[3] is overcome by the use of the cepstral method.

In the above example, the first step of the cepstral method is to subject the time-domain trace of Figure 10 to a CZT yielding the spectrum shown by Figure 12. The CZT permits selection of a spectral frequency range of 2.20 to 8.45 MHz tailored to the response characteristic of the ultrasonic transducer employed for the test.

Next, a further CZT is used to obtain the cepstrum shown by Figure 13 from the magnitude spectrum of Figure 12. The time range chosen for the quefrency abscissa is 0 to 5.12 microseconds to encompass the zero, first, and second order cepstral maximum. After identifying the approximate time position of the second order cepstral maximum on Figure 13 as 4 microseconds, the spectrum of Figure 12 is again subjected to a CZT for which a time range of 3.05 to 4.33 microseconds is selected. This transformation leads to the expanded trace of the second order cepstral maximum shown by Figure 14. Its 512 data points are spaced 1.28/512 microseconds or 2.5 nanoseconds apart. Since the time position of the cepstral maximum of second order represents the ultrasonic pulse transmission time multiplied by a factor of four, the resolution for determining the transmission time becomes 2.5/4 nanoseconds or 625 picoseconds.

A further improvement in time resolution can be attained if the measurement is based on a cepstral maximum of either third or fourth rather than second order in which case the resolution becomes 2.5/6 nanoseconds = 417 picoseconds or 2.5/8 nanoseconds = 313 picoseconds, respectively. Figures 15 and 16 show expanded displays for the third and the fourth order cepstral maxima and illustrate the earlier noted rise in the noise level that is associated with an increase in the order number of the cepstral maximum.

After carrying out a signal convolution to reduce amplitude fluctuations, the cleared up traces shown by Figures 17 and 18 are obtained for these maxima. The improved signal-to-noise ratio renders them more suited for an automatic electronic analysis.

In assessing the above cited error margins, it must be emphasized that they are valid only for small changes or differences in test specimen dimensions or ultrasonic propagation velocities. Also, to avoid potential errors of 2% to 3%, measurements that are to be compared must always be based on cepstral maxima of the same order number.

CONCLUSIONS

The principal advantage of the cepstral method of ultrasonic transmission time measurement is that it will function even in cases where, due to pulse distortions, the time intervals between ultrasonic indications cannot accurately be determined by a pulse overlap technique or similar procedures. It must be stressed, however, that the cepstral method will not eliminate the absolute errors that are inherent in all ultrasonic measurements of either specimen thickness or propagation velocity and are due to factors such as the transducer-coupling conditions (including the effect of a wear plate mounted in front of the piezoelectric element) and the peculiarities of the transducer radiation pattern. However, for a detection of relatively small differences or changes in specimen properties, and when conducted with closely controlled test parameters, the cepstral method offers a remarkable precision even under adverse circumstances such as high ultrasound attenuation in the test sample. Thus, with the cepstral method, one can determine even minute variations in specimen dimensions or ultrasonic propagation velocities caused, for instance, by mechanical stress or thermal effects.

Figure 1. First five back-surface echoes received from an 0.5-inch-thick aluminum plate. Linear amplitude scale (*arbitrary values*) versus horizontal time scale of 2.048 microseconds per division extending from 3 to 23.48 microseconds.

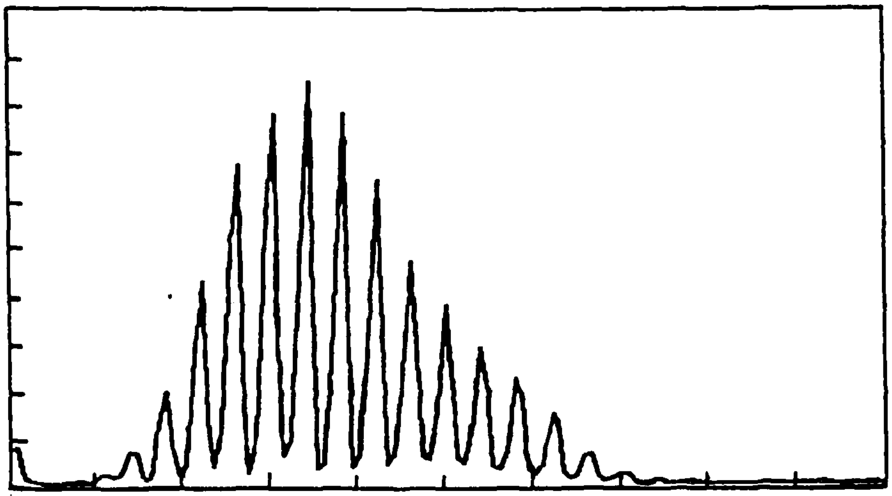

Figure 2. Magnitude spectrum obtained by an FFT of the ultrasonic multiple-echo signal of Figure 1. Linear amplitude scale (arbitrary values) versus horizontal frequency scale of 0.625 MHz per division extending from 0 to 6.25 MHz.

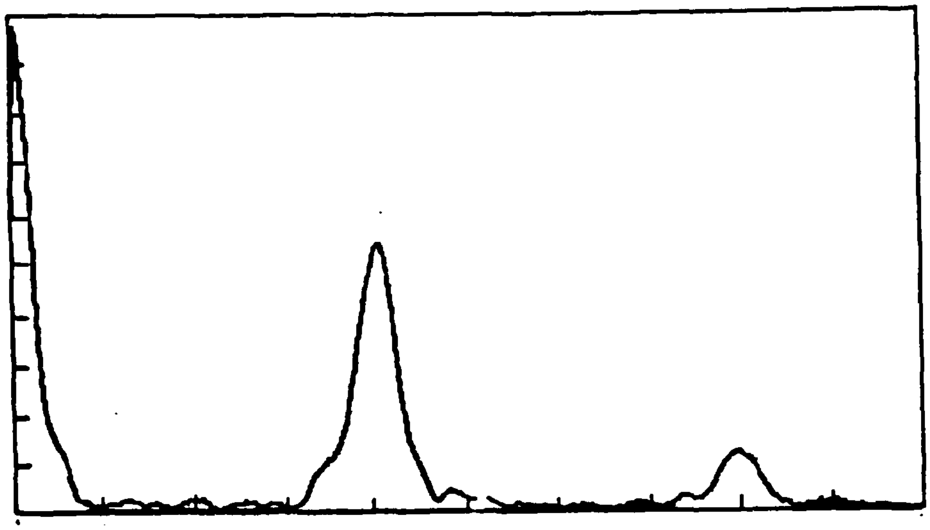

Figure 3. Cepstrum obtained by an FFT of the spectral function of Figure 2. Linear amplitude scale (arbitrary values) versus horizontal quefrency scale calibrated in 1.024 microseconds per division with a range of 0 to 10.24 microseconds.

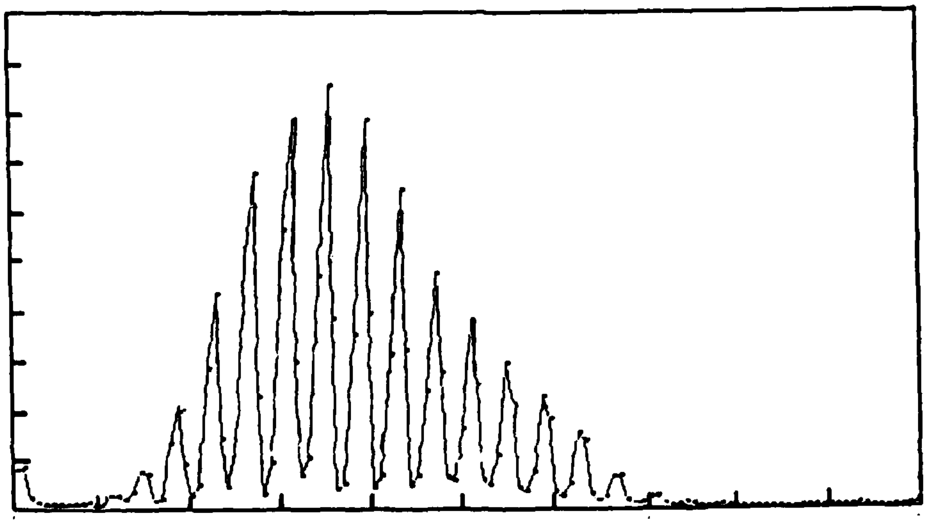

Figure 4. One-hundred and twenty-eight individual data points (connected by a thin line) representing the spectral function of Figure 2.

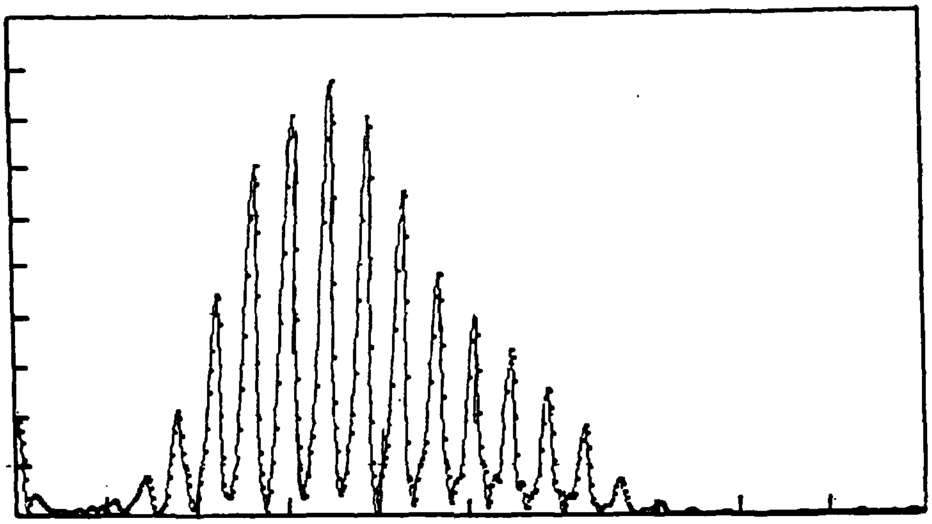

Figure 5. Five-hundred and twelve individual data points (connected by a thin line) representing the magnitude spectrum obtained by a CZT of the multiple-echo signal of Figure 1. Linear amplitude scale (arbitrary values) versus horizontal frequency scale of 0.625 MHz per division extending from 0 to 6.25 MHz.

Figure 6. Five-hundred and twelve individual data points (connected by a thin line) representing the cepstrum obtained by a CZT of the spectral function of Figure 5. Linear amplitude scale (arbitrary values) versus horizontal quefrency scale calibrated in 1.024 microseconds per division extending from 0 to 10.24 microseconds.

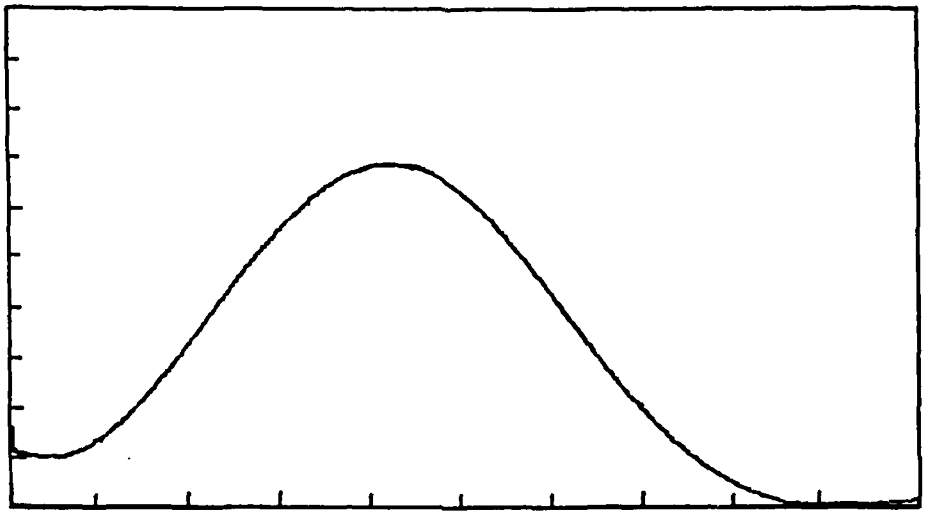

Figure 7. Expanded second order cepstral maximum of Figure 6 obtained by a CZT of the spectral function of Figure 5. Linear amplitude scale (arbitrary values) versus horizontal quefrency scale calibrated in 0.128 microsecond per division with a range of 7.55 to 8.83 microseconds.

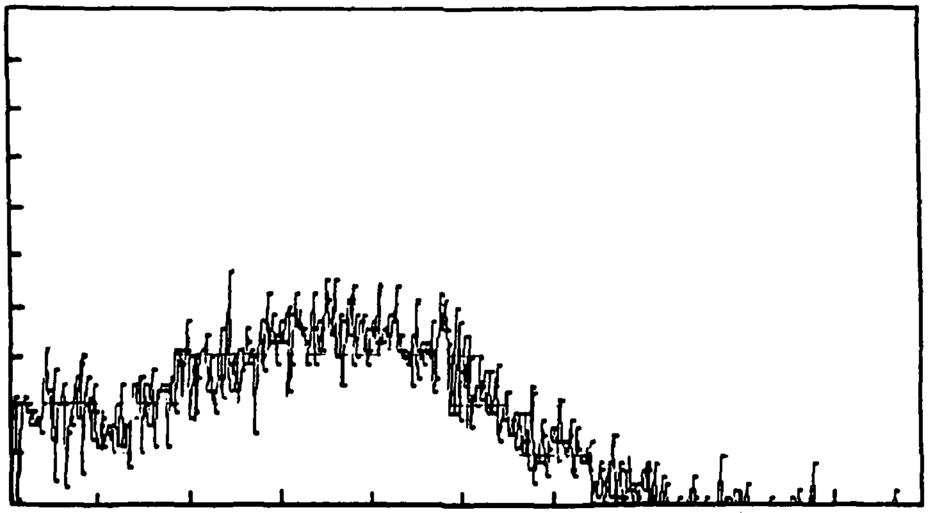

Figure 8. Expanded fifth order cepstral maximum obtained by a CZT of the spectral function of Figure 5. Linear amplitude scale (arbitrary values) versus horizontal quefrency scale calibrated in 0.128 microsecond per division with a range of 19.51 to 20 microseconds. Compared to Figure 7, noticeable increase in noise level.

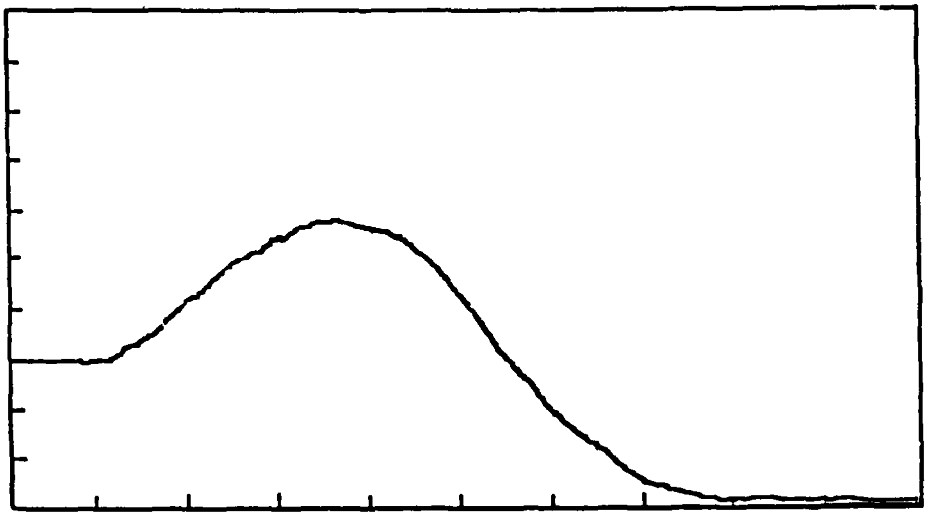

Figure 9. Fifth order cepstral maximum of Figure 8 after convolution to filter out noise.

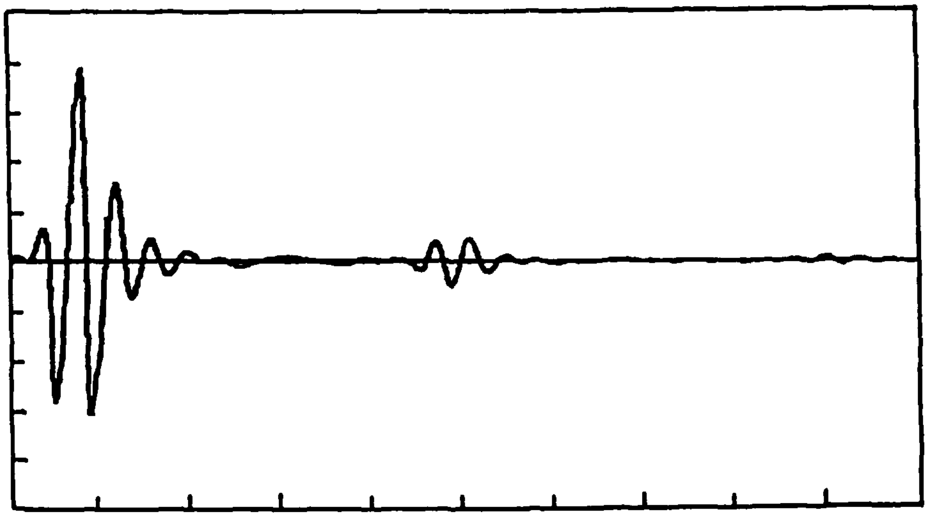

Figure 10. First three back-surface echoes received from a 0.5-inch-thick plate of composite material. Linear amplitude scale (arbitrary values) versus horizontal time scale of 0.512 microsecond per division extending from 2.00 to 7.12 microseconds.

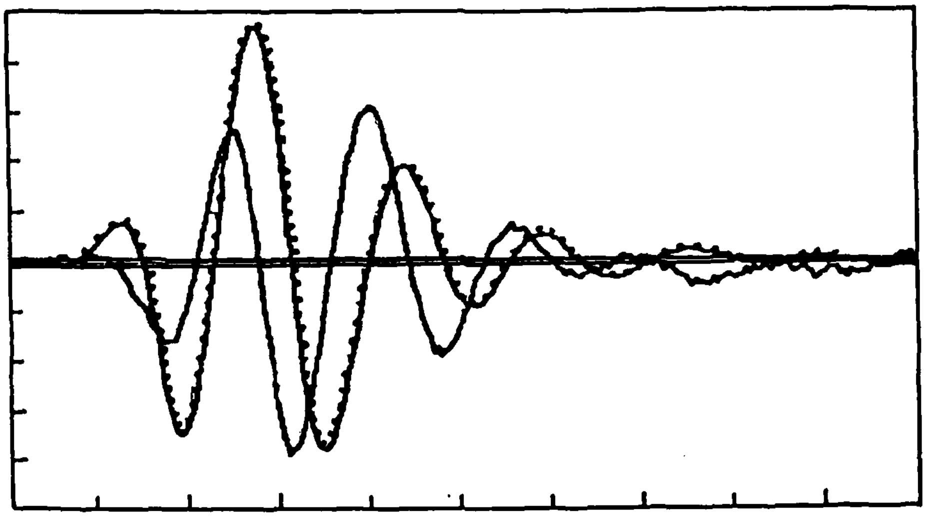

Figure 11. Expanded, superimposed display of the first and second back-surface echo of Figure 10. Linear amplitudes, height of the second echo six times enlarged relative to that of the first echo. Horizontal time scale of 0.128 microsecond per division. Trace of first echo is marked with dots and delayed by 2 microseconds relative to the trace of the second echo to effect overlapping.

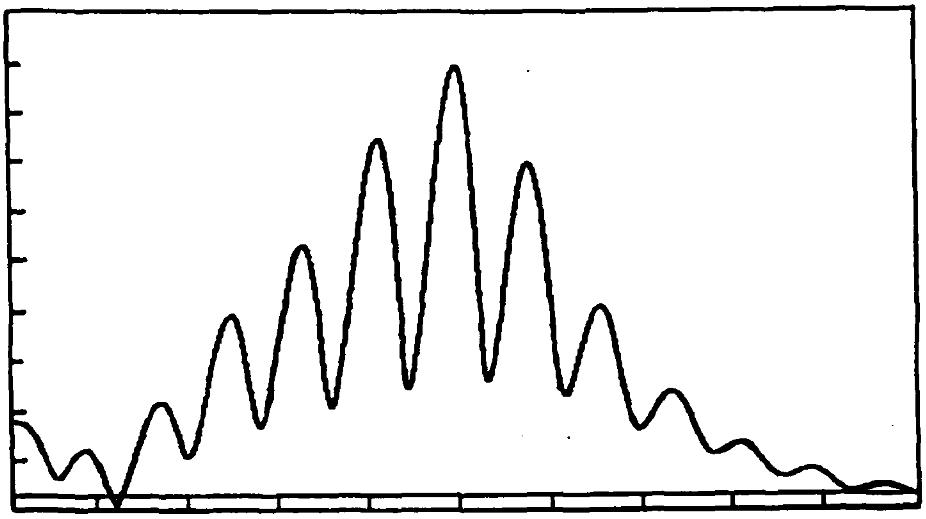

Figure 12. Spectrum obtained by a CZT of the multiple-echo signal of Figure 10. Linear amplitude (arbitrary values) versus horizontal extending from 2.2 to 8.45 MHz.

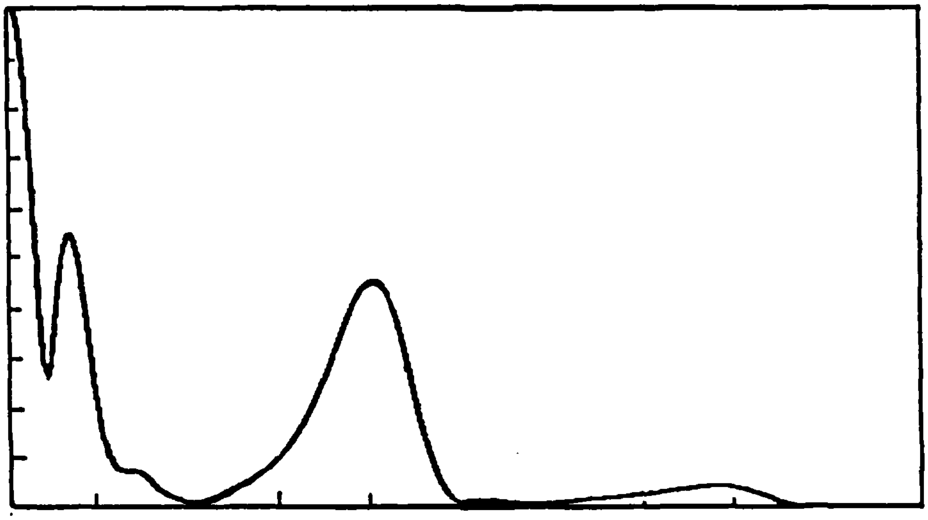

Figure 13. Cepstrum obtained by a CZT of the spectral function of Figure 12. Linear amplitude (arbitrary values) versus horizontal quefrency scale calibrated in 0.512 microsecond per division extending from 0 to 5.12 microseconds. Shown, are the zero order cepstral maximum with two peaks followed by the first and second order cepstral maxima.

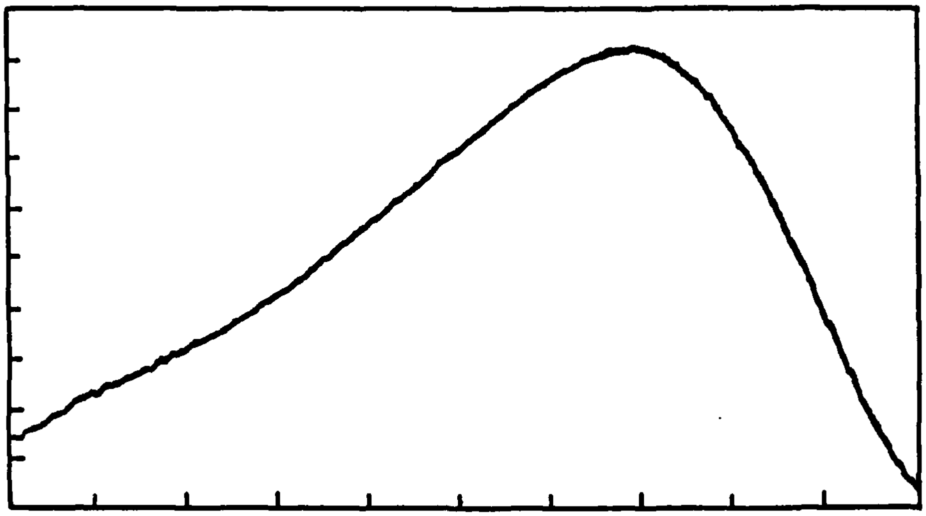

Figure 14. Expanded display of the second order cepstral maximum of Figure 13 obtained by a CZT of the spectrum of Figure 12 that yields a horizontal quefrency scale with a time calibration of 0.128 microsecond per division with a range of 3.05 to 4.33 microseconds.

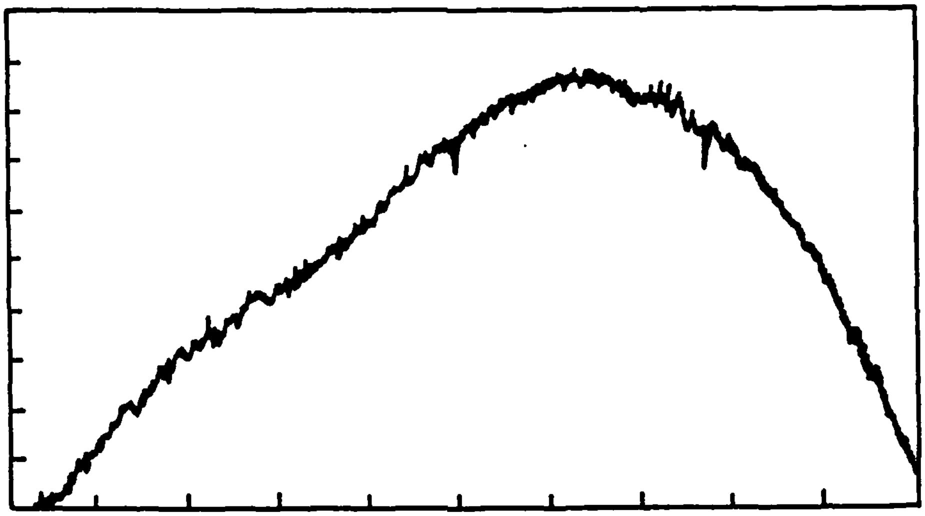

Figure 15. Expanded display of the third order cepstral maximum obtained by a CZT of the spectral function of Figure 12 that produces a horizontal quefrency scale calibrated in 0.128 microsecond per division with a range of 4.93 to 6.21 microseconds. Compared to Figure 15, noticeable increase in noise level.

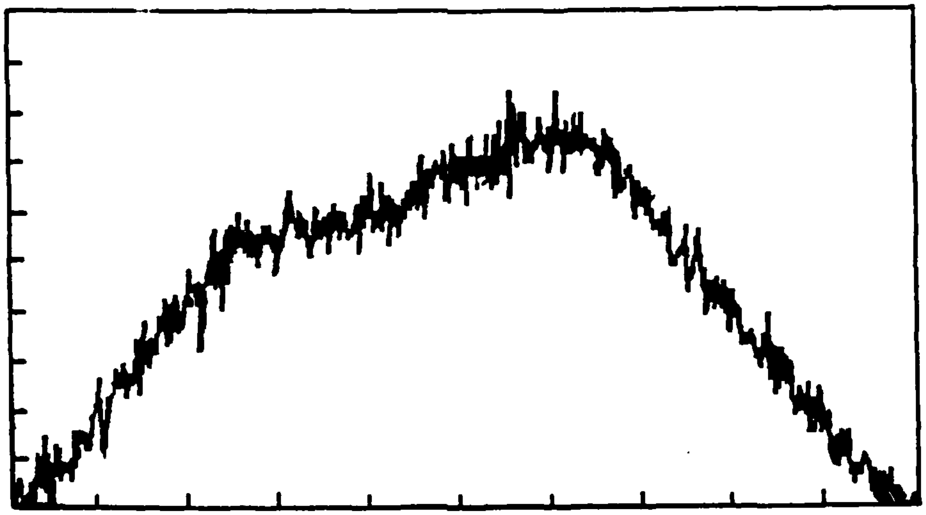

Figure 16. Expanded display of the fourth order cepstral maximum obtained by a CZT of the spectral function of Figure 12 which produces a horizontal quefrency scale calibrated in 0.128 microsecond per division with a range of 6.90 to 8.18 microseconds. The noise level of the signal is even higher than that observed in Figure 15.

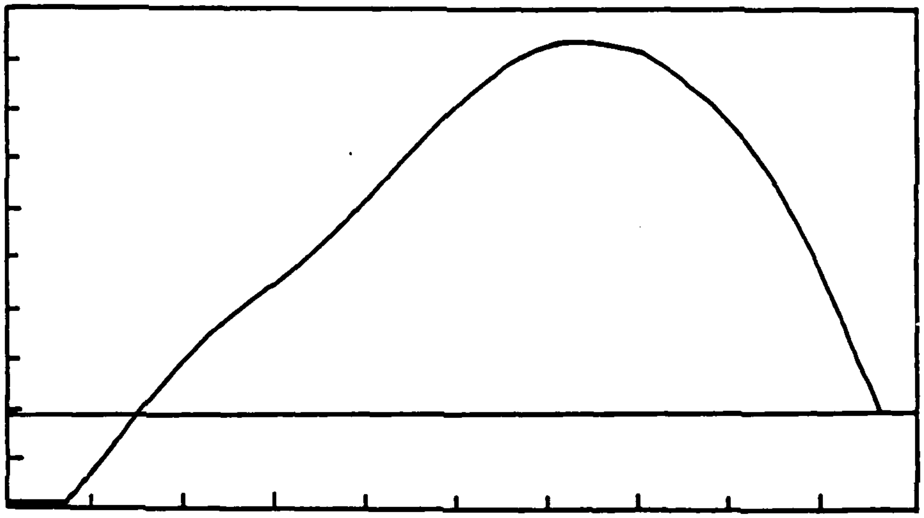

Figure 17. Third order cepstral maximum of Figure 15 after convolution to filter out noise.

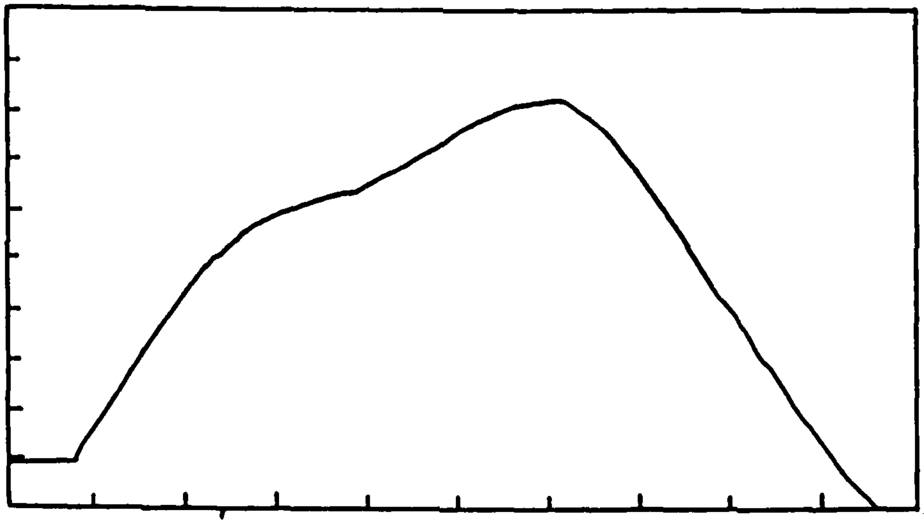

Figure 18. Fourth order cepstral maximum of Figure 16 after convolution to filter out noise.

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CEPSTRAL METHOD FOR THE MEASUREMENT
OF ULTRASONIC PULSE TRANSMISSION TIME
VARIATIONS - Otto R. Gericke

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Nondestructive testing
Ultrasonics
Data processing

A precise method for determining relative changes or small differences in ultrasonic pulse transmission times has been developed. The method uses multiple-echo signals obtained by injecting a pulsed, plane ultrasonic wave of the compressional mode into a sample with free, parallel surfaces. The ultrasonic transducer employed for this purpose acts as both transmitter and receiver. The received ultrasonic signals are subjected to two consecutive Fourier transformations to produce a cepstrum. The cepstral function derived from the multiple-echo signal exhibits characteristic maxima whose positions on the quefrency abscissa, after calibration in units of time, represent multiples of the ultrasonic transmission time. Since minute variations of this time can be determined from a shift in the position of a cep-stral maximum, the detection of very small changes or differences in sample thickness or ultrasonic propagation velocity becomes feasible.

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