THE ANALYTIC SIGNAL MAGNITUDE FOR IMPROVED ULTRASONIC SIGNATURES

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ABSTRACT

Conventional pulse-echo ultrasonic receivers rectify the received signal. Because the signature of the reflecting interfaces is modulated by the predominant ultrasonic frequency, interpretation of this signal in terms of the structure of the reflecting interfaces is difficult. Smoothing, as by an R-C filter, ameliorates this effect, giving a less confusing display at the expense of resolution.

The magnitude of the analytic signal, on the other hand, represents the shape of the energy packets arriving from the reflecting interfaces. Since this signature is free of modulation effects, interpretation of the signal in terms of the reflecting interfaces is more straightforward. Furthermore, smoothing is not normally needed.

The analytic signal magnitude can be obtained by several means. The implementation used in this study is particularly suited for digital data processing. The Hilbert Transform of the received signal (the "real part") is obtained with the aid of the Fast Fourier Transform. This produces the quadrature component (the "imaginary part"). The magnitude is calculated from both these components.

In contrast to signal processing techniques involving deconvolution, this technique is surprisingly robust with respect to noise and quantization. Typical signatures obtained with this technique are demonstrated.

INTRODUCTION

The ultrasonic A-mode signal provides the starting point for most ultrasonic systems. Although the A-mode signal is often not displayed, its characteristics, which are affected by the transducer, pulser, and receiver, nevertheless limit the quality of the final display.

Most commercial pulse-echo systems use full-wave rectification as part of the signal processing chain. Since there are only a few peaks in a single reflected pulse, the envelope is poorly defined. It is customary to smooth the signal by an R-C filter. This improves interpretability at the expense of resolution of closely spaced interfaces.

THE ANALYTIC SIGNAL

The analytic signal, which was defined by Gabor in 1947 (1) provides an alternative to rectification. Its magnitude has been shown to be related to the rate of arrival of the energy density (2). The significance of the time-energy concept was the topic of several papers at one of the sessions of the Fall 1980 Acoustical Society of America Meeting (3).

For a more extensive discussion of the analytic signal magnitude and its relations to ultrasonics, the reader is urged to refer to a recent journal paper by the author (4). Basically, the analytic signal is a complex signal whose quadrature components are related by the Hilbert Transform. Generally, the real quadrature component is taken to be the conventional signal, as would be observed on an oscilloscope. (Actually, the conventional signal may be any linear combination of the quadrature components.) One way in which the Hilbert Transform of any function can be obtained is to interchange the sine and cosine terms in the Fourier expansion, replacing $\cos \omega t$ by $\sin \omega t$ and $\sin \omega t$ by $-\cos \omega t$ (5).

EXPERIMENTAL VERIFICATION

Data were taken to compare this processing scheme with conventional rectification and filtering. A digital data acquisition system was used which digitized the unprocessed (raw r-f) ultrasonic signal. For comparison of the effect of the signal processing schemes, the same digital record that was used for analytic signal magnitude processing was also digitally rectified and smoothed.

The amplified echo was digitized using a Biomation 8100 transient recorder. This instrument was interfaced with a Digital Equipment Corporation LSI-11 microprocessor, which stored the data on diskettes and performed all of the later processing. The plots were produced using the graphics mode of the Diablo Hytype 1641 terminal. All programming was done in LABFORTH (6), which is an RT-11 resident version of FORTH (7,8). This language was chosen because assembly language routines can be written directly in the main program and because it offers the flexibility and immediate accessibility of an interpreter.

The A-scans were produced using a commercial pulser and receiver. The target consisted of a sheet of acrylic plastic, at a range of approximately 10 cm, which was carefully aligned to obtain the maximum specular echo. Because this experiment was concerned with biological applications, a 1 cm section of formalin-fixed hog liver was placed between the transducer and the target to simulate the general type of signal distortion (attentuation, refraction, and scattering) that is encountered when imaging through biological and other non-uniform media.

The data were digitized to 8-bit resolution at 10 ns intervals for records of 2048 points. A 2048 point real-valued FFT algorithm was used to compute the quadrature component by a Fourier Transform technique. The details of these calculations are explained elsewhere (4).

The results of three types of detection (rectification alone, rectification with smoothing, and computation of the analytic signal amplitude) are compared in Fig. 1, which shows the overlapping echoes from the front and back faces of the lucite. The echoes from the tissue, which would be far to the left of these traces, are not shown. Similar results were obtained when only water was in the path between the transducer and reflector. The results with tissue in the path are shown as they represent a more realistic case which includes distortions induced by the propagation media.

The absolute value of the received signal, which would be the result of the full-wave rectification with little or no smoothing, is shown in Fig. 1a. It is difficult to identify the precise location of the interfaces on this A-mode presentation.

Figure 1b is the result of applying an R-C filter, simulated by digital processing, to Fig. 1a. A time constant of 0.64 µs was used with a transducer center frequency of 2.25 MHz. This choice of a time constant produces a smoothing that represents a typical compromise: it is not quite enough smoothing to give a smooth rising edge to the signal, although it is high enough to produce a long trailing edge, which sacrifices resolution. A longer or shorter time constant would result in improvement of one of these aspects but degradation of the other. Note, incidentally, that smoothing delays the peak by approximately one-half cycle, as compared to Fig. 1a.

The analytic magnitude of the same signal, as shown in Fig. 1c, gives an A-scan that is easier to read than the rectified signal and has better resolution than the rectified and smoothed signal. This signal is much smoother than the signal that is only rectified and yet its peak occurs at approximately the same epoch. The analytic signal magnitude is expected to be the best measure of the time at which the peak occurs. Clearly, the two interfaces are most readily resolved by the analytic signal magnitude.

To answer the question of the suitability of this technique for the complicated echoes, such as arise in biological samples, the echoes from a section of excised injured cat spinal cord were studied. Figure 2 shows the digitized A-mode signal and the calculated analytic signal magnitude of such a specimen. The strong specular echoes are clearly resolved and the fine internal echoes can be seen. Since the processing scheme works for this biological system, it would also be expected to work well with the fine echoes from grain boundaries and other distributed reflections.

CONCLUSIONS

This study clearly demonstrates that the analytic signal magnitude provides better resolution than does either rectification alone or rectification with smoothing. In these experiments, the analytic signal magnitude was calculated by computer processing of sampled data, which demonstrates the utility of the method. Although digital implementation of such processing is currently prohibitively expensive, in a few years, production of a commercial clinical or industrial instrument incorporating this technique may well become commercially viable. Alternative implementations, using analog circuits, have produced equally good results.

The analytic signal magnitude has been successfully used in our laboratory for the production of images of biological specimens that include the soft internal echoes. This technique is expected to be particularly useful in those nondestructive evaluation applications where closely spaced echoes are to be resolved and where signature analysis is to be performed. The signature analysis would be aided by the fact that this signal represents the rate-of-arrival of energy from the specimen and is not affected by the phase characteristics of the transducer.

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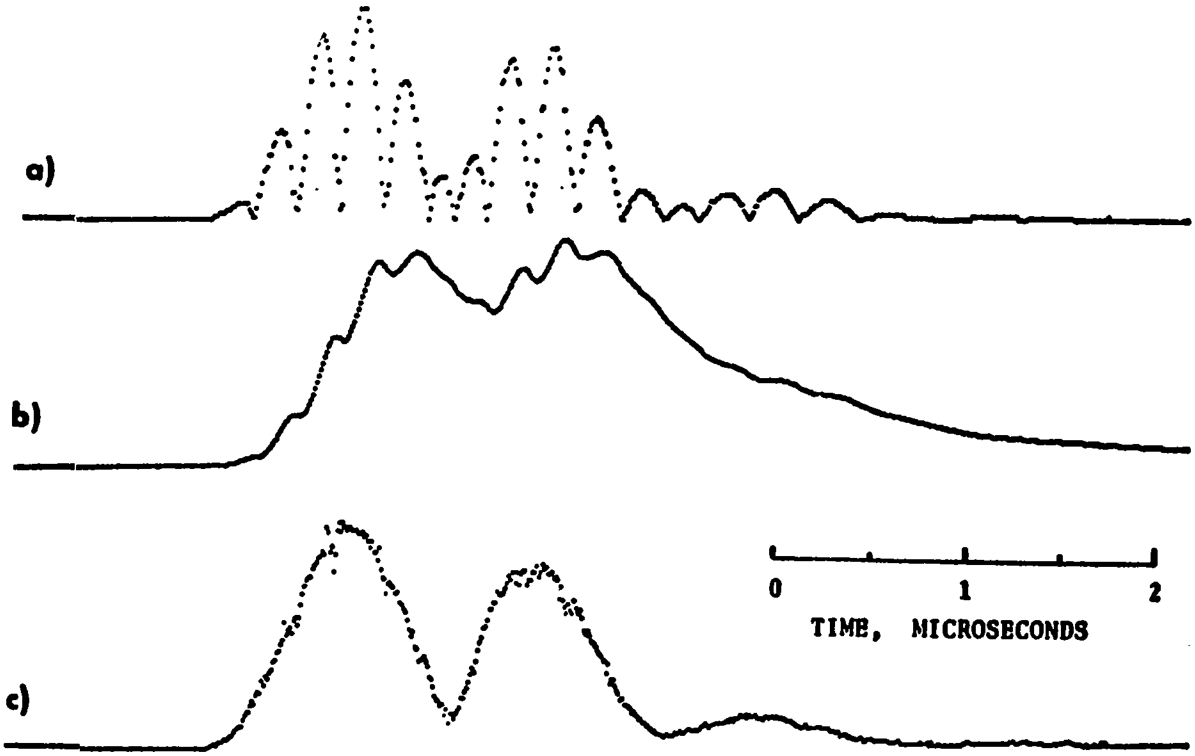

Fig. 1. Processed signatures of a signal from two closely spaced interfaces.

a) rectified

b) smoothed

c) magnitude of the analytic signal

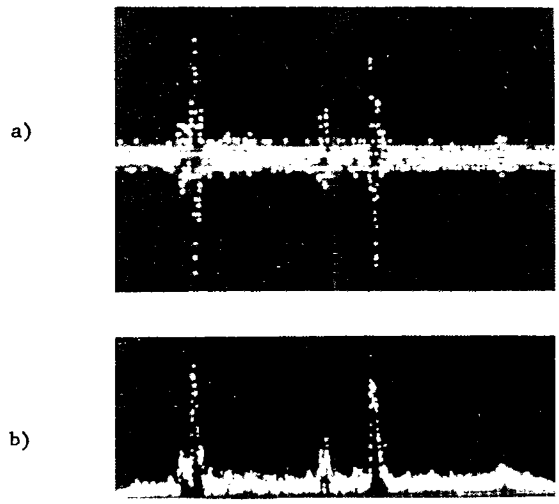

Fig. 2. Ultrasonic pulse-echo signal from an injured section of cat spinal cord.

a) unprocessed signal as digitized

b) result of analytic magnitude processing

The scans are aligned as to timebase.

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