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# A Modified Ultrasonic Pulse-Echo-Overlap Method for Determining Sound Velocities and Attenuation of Solids

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The ultrasonic pulse-echo-overlap method described by Papadakis [J. Acoust. Soc. Amer. 42, 1045 (1967)] has been modified to permit simultaneous measurement of the time delay and the relative voltage ratio between any pair of returning echoes in the pulse-echo train. All the components involved in the present modification are commercially available items, and this instrumentation system for the ultrasonic pulse-echo-overlap method is compatible with the pulse superposition method.

THE ultrasonic time-delay measurement developed by May[1] and Papadakis[2,3] offers a very useful alternative to the popular pulse superposition method described by McSkimin.[4,5] This method, referred to as the pulse-echo-overlap method, has the same potential for accuracy as McSkimin's scheme, but is generally easier to use. In addition, it can be used easily for measurements in highly attenuating or very thin samples where the pulse superposition method is difficult to apply. The pulse-echo-overlap method has been modified to permit simultaneous measurement of the time delay and the relative voltage ratio between any pair of returning echoes in the pulse-echo train. All the components of this method are commercially available items. The system is fully compatible with the pulse superposition method and differs from it by the addition of two components.

In the McSkimin pulse superposition method,[4] the pulse repetition rate of the rf oscillator is adjusted so that an echo within a particular pulse-echo train coincides exactly in time with an earlier echo in the next train. When this condition is achieved ultrasonic echoes of all orders are summed at the transducer to produce a voltage maximum in the rectified signal. In this way the repetition rate is a precise measure of the transit time between echoes. The main pulses are produced by a pulsed oscillator which is keyed by a pulse generator which is triggered, in turn, by a variable oscillator. During an experiment one adjusts the oscillator for an in-phase condition as seen by the superposition of video signals from all echoes on a cathode ray oscilloscope (CRO). In normal practice one tunes the triggering oscillator to the frequency which corresponds to one round trip of an echo through the crystal; this is the $p=1$ condition as explained by McSkimin.[4] One can also adjust the oscillator to half this fundamental frequency, thereby achieving a superposition of every other echo; this is the $p=2$ condition. In general, measurements made with other than $p=1$ are not as accurate and unambiguous as with $p=1$, except for such very low loss materials as quartz. Commercially available rf pulse oscillators such as the Arenberg PG650 are limited to a maximum pulse repetition frequency (PRF) of about 250 kHz. There are materials for which a round trip acoustic path of great length is impractical and therefore would require a PRF in excess of 250 kHz if the measurement is to be made with $p=1$. This is a practical problem for experimentalists, and

[1] J. E. May, Jr., IRE Nat. Conv. Rec. 6, Pt. 2, 134 (1958).
[2] E. P. Papadakis, J. Acoust. Soc. Amer. 42, 1045 (1967).
[3] E. P. Papadakis, J. Appl. Phys. 35, 1474 (1964).
[4] H. J. McSkimin, J. Acoust. Soc. Amer. 33, 12 (1961).
[5] H. J. McSkimin, J. Acoust. Soc. Amer. 37, 864 (1965).

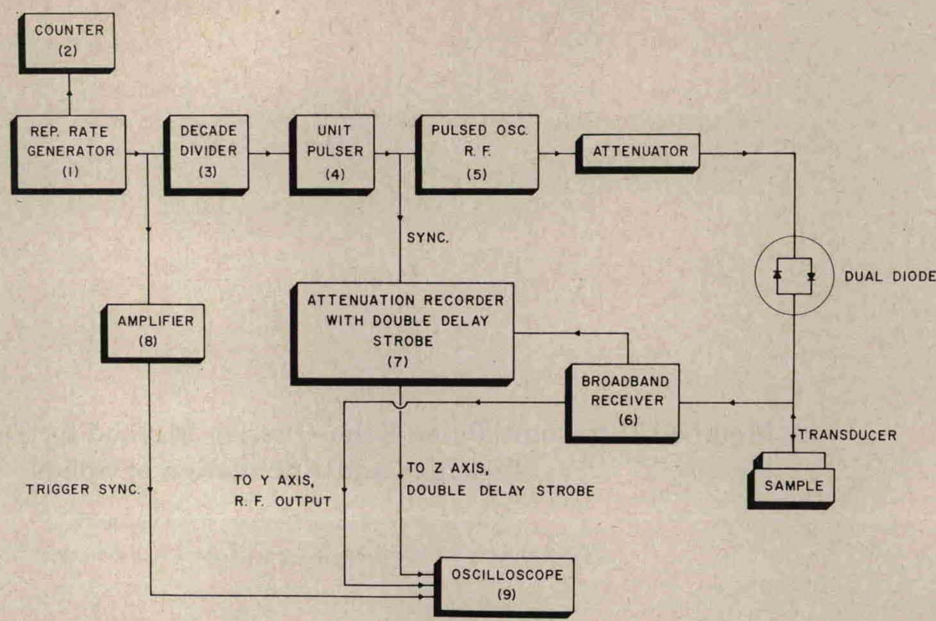


FIG. 1. Block diagram of a modified ultrasonic pulse-echo-overlap method. The components in current use are as follows: (1) Hewlett–Packard model 606B signal generator, (2) Hewlett–Packard model 524L electronic counter, (3) Airtech model DD-103 decade divider, (4) General Radio model 1217-C unit pulse generator, (5) Arenberg model PG-650C pulsed oscillator, (6) Matec model 5-30 MHz broad band receiver, (7) Matec model 2470 attenuation recorder, (8) Hewlett–Packard model 450A amplifier, and (9) Tektronix model 546 oscilloscope.

this problem led us to explore the possibilities of the pulse-echoe-overlap method developed by Papadakis.[2]

The ultrasonic pulse-echo-overlap method is in essence a variation of the well known pulse-echo method.[6–9] With a variable frequency repetition-rate generator, the CRO is triggered externally in time so that a cycle-for-cycle match of all echoes is seen. The triggering oscillator signal is divided down by 100 or 1000 and the divided output triggers the pulse generator, which, in turn, keys the rf pulsed oscillator. Operating the pulsed oscillator at a PRF which is an integral fraction of the CRO triggering rate is necessary in order to keep all main pulses in synchronism with all the echoes. In practice, there should be only one pulse train in the crystal at any time; the PRF rate of the pulsed rf oscillator should be then such that the previous pulse train has decayed into the noise level before the occurrence of another main pulse. If, however, one does not divide down the triggering rate for the pulsed oscillator, then the system operates in a mode equivalent to the pulse superposition method.

The proper overlapping of any pair of pulse echoes in a train is equivalent to the overlapping of all the echoes in the pulse train. This, of course, simplifies the CRO display. Matching will occur for PRF's corresponding to integral fractions of the delay time between the selected pair of echoes. The inverse of the lowest frequency to achieve a matching overlap is the delay time between the selected pair of echoes. Selective intensification of a pair of echoes is accomplished with a two-channel "strobe" delay generator triggered by the pulse generator and with output to the $Z$ axis of the CRO. The criteria for proper cycle-for-cycle matching of echoes have been discussed by Papadakis[2] in detail. In practice, the absolute accuracy of sound velocities measured by this method is correct within 0.02%, and change in attenuation can be measured with a resolution of 0.02 dB. Changes in round trip delay time can be measured with a sensitivity of two parts in $10^6$.

A general block diagram of the instrumentation is shown in Fig. 1. An important modification from Papadakis's original scheme is the use of the attenuation recorder

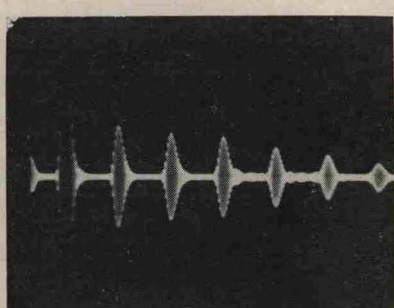

FIG. 2. Oscilloscope display of typical pulse-echo train. The material is quartz and the delay between echoes is 2 $\mu$sec. The carrier frequency is 20 MHz.

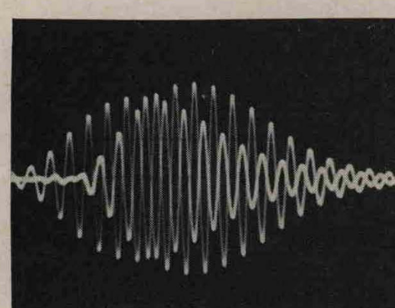

FIG. 3. Oscilloscope display of a pair of intensified echoes before final adjustment of triggering oscillator. The material here is quartz. The carrier frequency is 20 MHz.

[6] W. B. Daniels and C. S. Smith, in *The Physics and Chemistry of High Pressures* (Gordon and Breach Science Publishers, New York, 1963), p. 50.
[7] G. A. Alers and J. R. Neighbours, J. Phys. Chem. Solids **7**, 58 (1958).
[8] R. L. Roderick and R. Truell, J. Appl. Phys. **23**, 267 (1952).
[9] H. B. Huntington, Phys. Rev. **72**, 321 (1947).

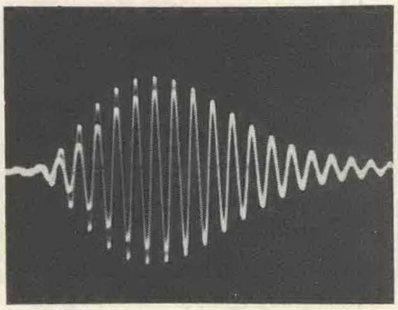

FIG. 4. Oscilloscope display of echoes 2 and 3 from Fig. 2 properly overlapped with respect to "in-phase" condition. The delay time between these two echoes is 2 μsec. The carrier frequency is 20 MHz.

Matec model 2470 unit to provide the double delay strobe to intensify the two rf echoes being monitored on the oscilloscope for velocity changes. The strobes simultaneously open two gates within the attenuation recorder so as to select from the entire echo train the video form of these same two echoes. Following peak detection, the logarithmic difference between the two selected echoes is measured and displayed on a built-in X–Y recorder.

The velocity measuring section of the system depends on the matching of the period of the repetition-rate generator to the round trip time in the sample. The output of this generator is divided down by a factor of 100 or 1000 to what may be considered a more normal repetition rate for ultrasonic pulse-echo equipment. The low frequency trigger is referred to as the Master Sync. For a preliminary setup, this Master Sync is used not only to trigger the rf pulsed oscillator and the attenuation recorder but also the oscilloscope. A conventional display of rf echoes, as shown in Fig. 2, is obtained. The time delays of the attenuation recorder may then be adjusted so that the output strobes intensify those two echoes to be monitored. The video output of the receiver may be displayed also on the dual display oscilloscope. An automatic gain control (AGC) circuit in the attenuation recorder may then be energized. This will maintain the first strobed (and selected) echo at a constant amplitude which is necessary for proper operation of the model 2470. The next step is to switch the oscilloscope $x$ axis to the output of the repetition-rate generator. Ideally, under these conditions, each echo is displayed on a separate sweep on the CRO. If the intensity is turned up, all the echoes will, indeed, be observed (providing a fast enough sweep is used so that sufficient retrace time is provided). As the intensity is slowly backed off, all echoes except the two being strobed will extinguish, and the display shown in Fig. 3 will be observed (only single channel operation should be used at this point). The frequency of the repetition-rate generator can now be critically adjusted for proper superposition, as shown in Fig. 4. Some difficulty may be experienced in obtaining proper scope synchronization because of the very high trigger rates and short recovery times available. It may then be necessary to apply the sinusoidal output of the HP-606B directly to the horizontal amplifier input. A satisfactory display can be obtained in this way. However, a triggered operation of the scope is preferable for two reasons: first, a linear sweep is obtained; second, a dual display operation of the scope is possible. In the dual display mode the rf echo output of the receiver may be applied to both vertical inputs and the scope attenuators adjusted so that both the monitored echoes have approximately the same amplitude. Such a display assists in adjusting the repetition-rate generator for exact phase overlap.

This modified method has several advantages over the pulse superposition method. The pulsed rf oscillator is driven at a relatively low PRF which insures stable operation. The CRO display consists of the rf overlap of *any* pair of returning echoes in the decaying pulse train (rather than the superimposed addition of all echoes in the train). While the pulse superposition method requires an echo train of at least 10 reasonable returning echoes for an accurate and unambiguous measurement, the pulse-echo-overlap method requires only two good echoes. The difference in CRO display allows accurate measurements of time delay in high loss materials. Another advantageous feature of the pulse-echo-overlap method is that the method allows an observation of the rf display directly rather than a video (rectified) display. Therefore, in practice, measurements are easier to make; the proper "in-phase" condition can be applied visually. In addition, the technique is no longer critically dependent on the shape of the pulse envelope.

The division factor of the triggering oscillator could be, in principle, $10^4$ or even $10^5$ which would allow measurements of velocity in extremely thin samples subject only to the limitations imposed by the loaded Q of the transducer. It is concluded that the modified ultrasonic pulse-echo-overlap method (after Papadakis) allows one to make accurate measurements of the acoustic velocity for extremely small samples and offers the only technique presently available to isolate and study the phase shift due to the transducer–sample bond. The method discussed here provides for simultaneous measurement of acoustic attenuation and velocity of elastic waves.

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