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SPEED AND ATTENUATION OF ULTRASONIC WAVES FROM CHIRP MEASUREMENTS

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Abstract
This paper describes the design and operation of a new ultrasonic measurement system that uses a long-duration signal source (*chirp*) for measuring the propagation and attenuation of ultrasonic waves in core samples. Compared to standard systems, which utilize short-duration pulses, the new technique allows better signal-to-noise ratios. Our results show that the chirp is a practical alternative to conventional pulses for laboratory measurements.

Introduction
Standard systems for measuring ultrasonic parameters in solids depend upon the excitation and observation of short-duration pulses. This technique is simple to implement and the received signals are usually easy to interpret, at least in terms of time-of-flight. On the other hand, because all of the acoustic energy used to make the experiment must be emitted from the source transducers in just a few microseconds, it is relatively hard to increase the emitted power beyond applied signals levels of a few hundred volts.
These considerations have led the seismic exploration industry to develop an extensive technology for measuring time-of-flight and, to a lesser extent, attenuation using a variety of long-duration signal sources (Geyer, 1989). The best known of these signal types is a swept-frequency, or *chirp*, source. Our system is built around that technology.

Experimental Set-up
Fig. 1 shows the major electronic elements and the signal routing for the system we used.

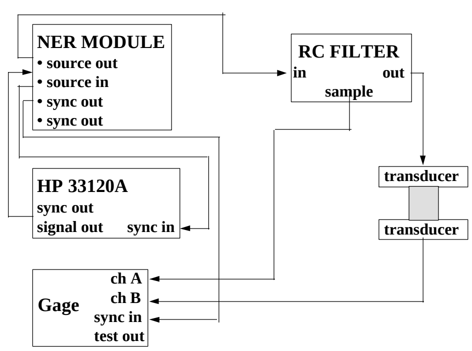

Fig. 1: Schematic diagram of the measurement system

Chirp source signals are generated by an HP 33120A function generator. This device provides a fairly wide range of both linear and logarithmic swept-frequency signals of the form $f(t) = A \times sin[w(t) \times t]$, where $w(t) = At+B$ for linear sweeps, and $w(t) = A+B \times log(t+1)$ for logarithmic sweeps. After generation, the signal is routed through a module constructed by New England Research Inc. (NER). It passes to the source transducer through a two-stage 15 kHz RC filter. A 10× sample of the filtered output is routed to the oscilloscope's channel A for recording; the signal from the receiver transducer is sent directly to the oscilloscope's channel B.

Signal Processing

In a typical measurement we record between 64×10^3 and 512×10^3 samples, at a rate of 30×10^6 samples per second, for both the driving signal (provided by the generator) and the received signal. Although these two signals contain a great deal of information about the elastic response of the sample between the transducers, that information is not in a useful form. To extract this information, we must process the recorded signals to synthesize the response of the sample to an impulse signal.

The simplest processing is cross-correlation of the source and receiver traces. If *s(t)* is the source signal and *r(t)* is the received signal, the correlated trace is computed from

$$c(t) = \int_0^\infty r(t+t)s(t)dt \tag{1}$$

This processing computes the impulsive signal we would have recorded if the input pulse shape had been the *autocorrelation* of the source chirp signal with itself. We implement this computation in the Fourier domain using the transform of equation 1:

$$c(w) = r(w)\tilde{s}(w) \tag{2}$$

followed by an inverse transformation (Mathews and Walker, 1965). Because of the speed of the Fast Fourier Transform, this algorithm is actually much faster than a direct (time-domain) implementation of equation 1.

Results and Discussion

Time Domain Measurements

We performed a suite of measurements with standard sample types (Aluminum and Lucite). This section reports some of our results. Fig. 2 shows data for an aluminum sample.

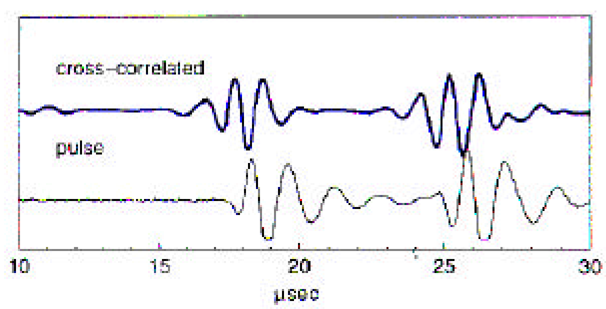

Fig. 2: Wave-form data from a one-inch aluminum sample for a compressional p-wave. The lower trace is a pulsed measurement; the other trace is the result of cross-correlation processing of a 2 ms linear sweep from 1 kHz to 5 MHz through the same sample.

In comparing pulse-mode traces with cross-correlated traces, it helps to understand that in pulse-mode measurements we expect to see a sharp first arrival at the beginning of the pulse. In cross-correlated traces, on the other hand, we expect to see a more-or-less symmetrical pulse shape centered on the pulse arrival time. Using these results, we compared time-of-flight measurements from pulse-mode measurements with those of cross-correlation processing. Table 1 shows the event times picked from cross-correlated linear-sweep *p* and *s* traces with several (trapezoidal) filtering choices as well as results from a conventional pulse-mode measurement.

Filter	Head-to-Head time (μs)		Sample data (μs)		Speed (m/s)	
	p	s	p	s	p	s
wideband	13.71	24.36	17.67	33.61	6417	2745
1-1.5-5-7 MHz	13.73	24.52	17.75	32.57	6318	3155
2-3-8-10 MHz	13.71	24.53	17.72	32.54	6334	3171
pulse-mode	13.47	24.48	17.48	32.57	6334	3133

Table 1: Transit times and velocities for a one-inch aluminum sample. The first three lines of the table show the arrival times for both head-to-head and sample data and the inferred velocities computed using the center point of linear sweep data processed by cross-correlation. The last line shows the corresponding values for conventional pulse-mode measurements.

As we see, the velocity measurements from pulse-mode and the two filtered cases show good agreement in time-of-flight. The wideband (unfiltered) sweep deviates substantially more.

Spectral Measurements

In order to investigate power spectral properties of these measurements, we compared data shot across a one-inch aluminum sample to data for a one-inch Lucite sample. We restricted our attention to the *s*-wave type and we only examined pulse-mode data and sweeps with a duration of 2 ms. After cross-correlating the sweep traces, we extracted a 20 ms long region centered at each of the resultant pulses and computed the amplitude spectrum.
Fig. 3a shows the amplitude spectra for the aluminum pulses; Fig. 3b shows the logarithm of the ratio of the spectral amplitudes for aluminum vs. Lucite.

Although we show the ratio for a wide frequency range, it is only well posed over about 400 kHz to 1.4 MHz. We can estimate the Lucite Q-factor, Q_{luc}, from these curves by using a spectral ratio technique, described in (Toksoz *et al*., 1979). As an example, we show in Fig. 3b the result of a least-square fit to a portion of the spectral ratio for a linear sweep. The fit provides:

$$\log_{10}\left(A_{al}/A_{luc}\right) = 0.417 \times 10^{-6} f - 0.008$$

where the frequency *f* is in Hz. The *Q*-factor of Lucite, on the other hand, comes from:

$$\ln\left(A_{al}/A_{luc}\right) = pft/Q_{luc} + G$$

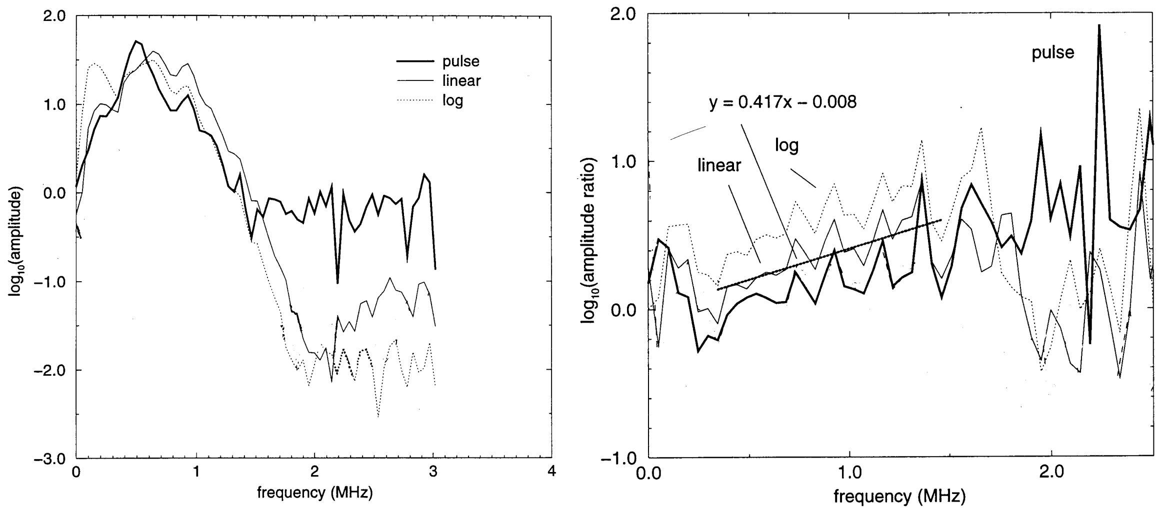

Fig. 3: a) Amplitude spectra for a shear wave arrival across a one-inch aluminum sample using pulse, linear sweep and logarithmic sweep. b) Logarithm of the ratios of the spectral amplitudes of shear waves traversing one-inch aluminum and Lucite samples. Each curve shows the ratio for data taken by one of the three methods examined in this paper: pulse, linear and logarithmic sweep.

where $t = 50\times10^{-6}$ is the travel-time through Lucite, G is a constant which we can ignore, and we have assumed that aluminum has an infinite Q-factor. Since $\log_{10} x = 0.434 \ln x$, we find: $Q_{luc} = 160$. Repeating for each of the available methods gives: pulse = 183; linear sweep = 160; log sweep = 157.

All of the results were based on correlation processing. We also tried a few computation with Aluminum and Lucite using strong fourier decon, but the results showed no obvious improvement in spectral coverage.

Conclusions

In comparing chirp and conventional pulse measurements, good agreement was observed both in time-of-flight and amplitude spectra, with consequent similar velocity and attenuation values. In the amplitude spectra, the chirp measurement shows a substantially lower high-frequency plateau. We think that this indicates that the amplitude signal-to-noise ratio for the chirp method is an order of magnitude greater than that for the pulse method.

References

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