PARAMETRIC BEAM FORMATION IN ROCK

P. A. Johnson and T. M. Hopson
Geological Engineering Group MS D443
Los Alamos National Laboratory
Los Alamos, NM 87545

B. P. Bonner
Earth Sciences Department
Lawrence Livermore National Laboratory
Livermore, CA 94550

T. J. Shankland
Geophysics Group MS D447
Los Alamos National Laboratory
Los Alamos, NM 87545

INTRODUCTION AND BACKGROUND

The highly nonlinear elastic properties of rock may enable a new means of imaging Earth structure through parametric formation of a difference frequency beam from the interaction of two collimated primary elastic waves. Because the difference frequency beam can have the narrow collimation of the higher frequency primaries, it could be used as a directional wave source. Such a low frequency wave propagates farther than the primary signals to locate features not currently detectable by waves generated from conventional sources. The concept of a nonlinearly-derived source arose from research in underwater acoustics [1] where the idea of beating collinear high frequency beams to produce a collimated beam at the lower, and less attenuated difference frequency originated; this work led to the development of nonlinear, directional sources in water [2].

The large elastic nonlinearity of rocks is due to the network of microfractures they generally contain; as these cracks close with applied stress, there are correspondingly large changes in elastic moduli [3]. The change in a modulus M with pressure P, dM/dP, can be nearly two orders of magnitude larger in rocks than in an uncracked material such as a liquid or crystal. Nonlinear conversion efficiency from primary to difference frequency signals increases with dM/dP and is therefore higher for rocks than for uncracked materials [4]. However, the enhanced nonlinear conversion is partially diminished by the large elastic wave attenuation also characteristic of rocks [3].

The purpose of this paper is to show how nonlinear elastic waves generated within a material can be made to interfere and produce a strong difference frequency signal at distances where the primary signals have disappeared due to attenuation. In addition, we show results from low frequency attenuation studies using a torsional oscillator [5,6] aimed at determining the microstructural properties that control the nonlinear response in rock, with the goal of improving parametric array generation and understanding where the departure between linear and nonlinear elasticity takes place in rock. Lastly, we demonstrate a sensitive, low noise frequency domain travel time (FDTT) method for application with the parametrically-generated difference signals. The FDTT method is of general applicability for accurate measurements of travel time in the presence of noise [7,8,9].

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 11
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1992

EXPERIMENTAL METHOD AND APPARATUS

Experimental configurations for the parametric array, torsional oscillator, and the FDTT method are described in this section. The experiments showing parametric array formation and those illustrating the FDTT method took place in a 183 cm-long sample of Berea sandstone. For the torsional oscillator measurements a 20 mm-long sample of Sierra White granite was employed. Because of their elastic uniformity both rock samples are standard materials in rock physics experiments .

Parametric Array Measurements

For the parametric array measurements we use the configuration shown in Fig. 1. The two primary-wave signals are electronically summed inside the function generator, amplified, and fed into a single transducer. The transducer injects two approximately planar, collinear waves propagating with separate frequencies, whose interaction creates the difference frequency signal. The detected signal is preamplified and recorded on a digital oscilloscope, and then relayed to a SUN SparcStation for processing [10].

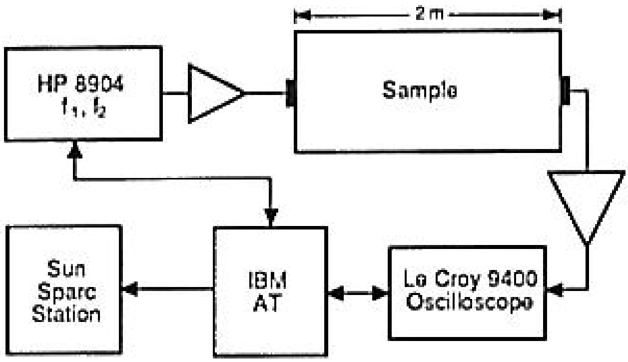

Fig.1. Experimental configuration of parametric array measurement.

Torsional Oscillator Measurements

The torsional oscillator experiment was designed to quantify the departure from linearity as a function of strain, and to test whether or not a material can be made more nonlinear by inducing additional microcracks. Both amplitude dependent attenuation and the strength of the nonlinear interaction are thought to result from the presence of microcracks. Therefore, if strain dependent attenuation can be increased by oscillating the sample in torsion at high amplitude, the relation between nonlinear attenuation and microcrack density is firmly established because new microcracks are produced by fatigue damage. Higher microcrack density should then improve parametric array formation by increasing the elastic nonlinearity.

In these experiments, a sample is oscillated in torsion over a range of strains from 10^{-7} to 10^{-4} at a frequency of 1 Hz (the torsional oscillator operates between 0.1 and 100 Hz). Shear attenuation is a direct function of the phase angle between torque and twist as a function of frequency and amplitude. For a complete description of the experimental configuration see Bonner and Wannamaker [6].

Frequency Domain Travel Time Measurements

The FDTT measurement is based on measuring the phase difference between the nonlinearly-derived difference frequency wave produced in a rock sample and an electronically derived reference signal. A more theoretical discussion of the method is described in Johnson et al. [9].

Fig. 2 is a block diagram of the experimental apparatus for measuring travel times of parametrically-created waves. Frequencies f_1 and f_2 are summed inside the function generator before being fed to the compressional wave source transducer and also to a high frequency, low noise mixer (multiplier), denoted "first mixer" in the figure. The mixer output is the product of the two input signals, which can be expressed as a superposition of signals at the sum and difference frequencies. A low-pass filter attenuates the sum frequency and leakage of the primary frequencies from the mixer output leaving only the difference frequency. This electronically produced difference frequency signal is then fed to a second mixer. The other input to the second mixer is the amplified signal output from nonlinear mixing of waves in the sample, also low-pass filtered. The output of the second mixer is a dc voltage whose amplitude depends on the phase delay as a function of frequency or wave vector between the two input difference frequency signals. As one of the primary frequencies is swept stepwise in frequency, the phase difference between the difference frequency wave produced in the rock and that produced electronically creates an interference signal in the second mixer which is recorded using a digital voltmeter. The interference frequency is inversely proportional to the travel time of the difference frequency wave propagating through the rock. If any later arrivals are present, the interference signal will be a summation of characteristic oscillations corresponding to all arrivals. [Of interest to NDE ultrasonic applications is that travel times of a single-frequency primary wave across a rock sample can be measured by using a single mixer. Here the electronic signal with no phase delay is mixed with the phase-delayed signal that has traversed across the rock sample, again producing a dc level that oscillates as frequency is swept stepwise. This travel time is obtained independently of that from the difference frequency wave. These results are discussed in detail by Johnson et al. [9].

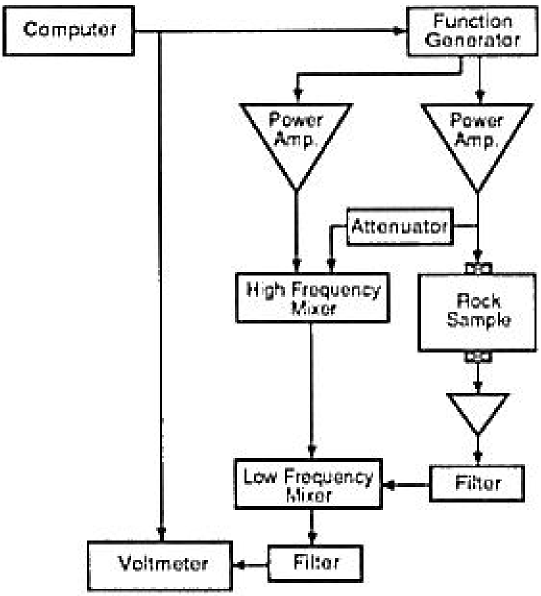

Fig. 2. Experimental configuration of frequency domain travel time measurement.

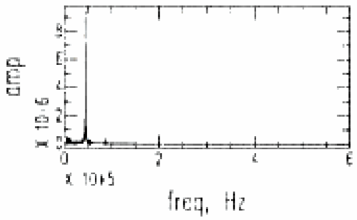

Figure 3. Spectral plot of recorded signal across 183-cm long sample when primaries were fixed at 555 and 559 kHz. Amplitude in arbitrary units.

RESULTS

Parametric Array Measurement

A significant result of this paper is in Fig. 3, which illustrates the strong parametric generation of a difference frequency signal in sandstone. The figure shows an example of the measured spectrum when the primary wave frequencies were fixed at 555 and 559 kHz, respectively, and thus the difference frequency was 44 kHz. It is remarkable that because of frequency dependent attenuation there is no trace of the primary wave signals while the difference frequency and the second harmonic of the difference frequency remain strong, despite the fact that the conversion efficiency between primary waves and the difference wave is on the order of 1% [2]. For this sample the specific dissipation Q, which is inversely proportional to attenuation, is approximately 70.

Torsional Oscillator Measurement

In Fig.4 the phase angle between the torque and twist is shown for the granite as a function of shear strain amplitude, before cycling (dots) and after 10^7 cycles (solid triangles) at a strain of 3×10^{-5}. The departure from linear to nonlinear elastic behavior is shown to take place at strains of greater than approximately 6×10^{-6} for the sample of Sierra White granite. The strain sensitivity of the attenuation increases dramatically as a function of higher strains.

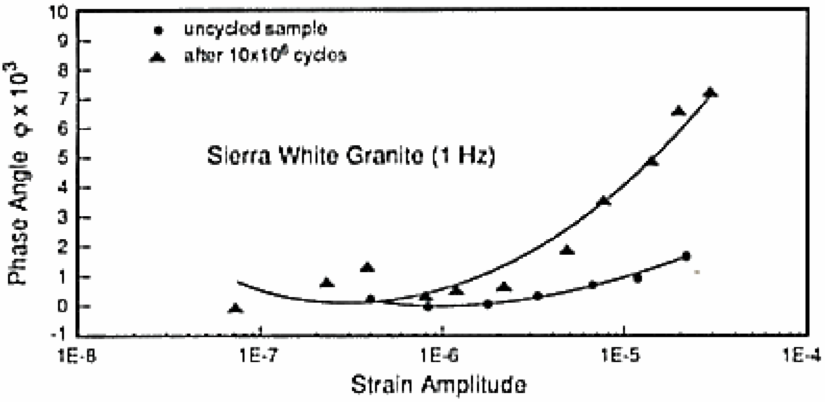

Figure 4. Torsional oscillator result.

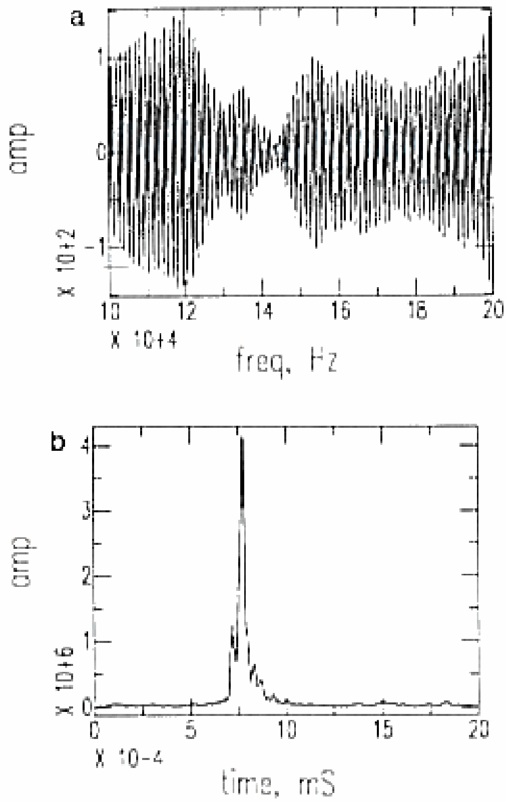

Figure 5a. dc voltage versus frequency where f_2 was swept from 100 to 200 kHz and f_1 was fixed at 350 kHz, and propagation path length was 183 cm. (5b) FFT of 5a. Measured travel time of the difference frequency signal was 79 milliseconds. Amplitudes in arbitrary units.

Phase Measurements

Results of the FDTT measurement are shown in Figure 5a. Measurement of the characteristic cycle can be made in several ways, but the best way is to transform the interference signal into the time domain and measure peaks corresponding to arrival times (Figure 5b). The first lower amplitude peak corresponds to the direct arrival. The direct travel time across the sample is at approximately 79 milliseconds. The large peak following the direct arrival is due to constructive interference of two side-wall reflections arriving simultaneously. Arrivals from two other discrete scatterers can be seen following the large amplitude arrival.

DISCUSSION

The foremost result from our current work, shown in Fig. 3, is that producing a directed, nonlinear-wave source at the difference frequency may well be possible in the earth. Careful measurements were conducted using the identical experimental configuration but without the rock (transducers were face-to-face) to be certain that the difference frequency was created in the rock and not in the associated electronics and/or transducers.

The torsional oscillator experiment shows that introducing additional cracks into rock increases the nonlinearity of the material significantly. This work implies that damaging the near-source region should enhance parametric array formation which may be useful in Earth imaging studies. The possibility of using a fractured ceramic for creation of a parametrically-derived difference frequency signal outside of the material under study and then injecting it into the material is intriguing. NDE applications of a directed source may be in imaging large dissipative structures such as bridge pillars, or in calculation of nonlinear coefficients to monitor progressive fatigue (e.g.[11]).

Advantages of the FDTT method over conventional ultrasonic methods is primarily the low-noise data collection capability it offers. This results from the shifting of the signal of interest (which is at the difference frequency) to dc away from the generally higher frequency noise. Additionally, the effective signal-to-noise ratio is increased because the interference signal, which is continuous, contains numerous, repetitive oscillations from which travel times can be precisely measured. Finally, the fact that arrivals separate distinctly upon inverse Fourier transforming the characteristic oscillation signal is a distinct advantage over most other methods. The principle of the FDTT measurement of direct and reflected beams is an innovation in acoustics as significant as the nonlinearity itself.

CONCLUSIONS

Most notably, when two collinear, primary pressure waves were simultaneously injected into a 183-cm long sample at ultrasonic frequencies, we detected strong difference frequency signals across the sample but found that the higher-frequency primary waves had been entirely attenuated. We also showed that the nonlinearity of the material could be increased by inducing additional cracks. We conclude that the possibility of creating a low frequency, directional source by nonlinear elastic wave mixing is promising for laboratory and field applications.

Finally, we developed a sensitive, frequency domain travel time (FDTT) method for measuring travel times of the difference frequency signals propagating across a sample. This method is of general applicability for accurate measurements of travel time in the presence of noise.

ACKNOWLEDGEMENTS

This work was supported by the Office of Basic Energy Science of the Department of Energy under contracts W-7405-ENG-36 (Los Alamos National Laboratory) and W-7405-ENG-48 (Lawrence Livermore National Laboratory) with the University of California.

REFERENCES

1. P. Westervelt, J. Acoust. Soc. Am., 35, p. 535 (1963).
2. T. G. Muir, in Science, Technology and the Modern Navy, 30th Anniversary 1946-1976, edited by E. I. Salkovitz, Department of the Navy, Office of Naval Research, Arlington, Va., p. 548 (1976).
3. K. W. Winkler, A. Nur, and M. Gladwin, Nature 277, p. 528 (1979).
4. L. H. Taylor, and F. R. Rollins, Jr., Phys. Rev. Ser. A., 136, p. 591 (1964).
5. B. P. Bonner and B. J. Wanamaker, in Review of Progress in Quantitative NDE, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York and London, 1990) Vol 9B, p. 1709.
6. B. P. Bonner and B. J. Wanamaker, in Review of Progress in Quantitative NDE, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York and London, 1991) Vol 10B, p. 1861.
7. P. A. Johnson, T. M. Hopson, and T. J Shankland,EOS Trans. Am. Geophys. Union 72, p.285, (1991a).
8. P. A. Johnson, A. Migliori, and T. J. Shankland, J. Acoust. Soc. Am 89, p. 598 (1991b).