

## Differential Acoustical Resonance Spectroscopy: An experimental method for estimating acoustic attenuation of porous media

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### Summary

A new acoustic method of estimating attenuation in rocks is presented. This method, called Differential Acoustic Resonance Spectroscopy or DARS, uses the perturbation caused by a small sample of rock to the  $Q$  and resonant frequency of a fluid-filled cavity resonator. The changes in the resonant frequency and quality factor are interpreted to characterize the velocity and attenuation properties of the rock sample. The frequency of DARS operation is determined by the size of the fluid-filled cavity, not the size of the rock sample; therefore, DARS can be used to measure an acoustically small sample in the laboratory at relatively low frequencies. Moreover, the sample may be irregularly shape so long as its size is small in comparison to the cavity volume. This paper describes the DARS concept, theory of operation, and some attenuation results for small porous samples at a frequency near 1 kHz.

### Introduction

Two challenges make it difficult to draw solid conclusions regarding the use of attenuation to interpret field data: (1) Inherent difficulties with measuring attenuation with current laboratory techniques; and (2) the difficulty of frequency scaling to the band of interest where different attenuation mechanisms may dominate in comparison to the band of the particular lab measurement. Both pulse transmission/ reflection and resonance bar techniques can give reliable estimates, but pulse techniques operate in the hundreds of kilohertz range and resonance bar techniques usually require large samples or time-consuming sample preparation (Boubie, 1987). We developed DARS to estimate attenuation on small samples of rocks in the laboratory at frequencies applicable to field seismic and logging experiments, e.g., around 1 kHz. Moreover, we expect to use DARS to develop a better understanding of attenuation and its relationship to the fluid flow properties of porous media.

The essential concept of DARS is the perturbation caused by the introduction of a rock sample. The DARS cavity resonator can be spherical, rectangular, cylindrical, or any other shape. We used a fluid-filled cylindrical resonator as illustrated in Figure 1. The lowest resonant frequency of longitudinal mode in the cylindrical cavity is approximately given by the well-known formula:

$$f = \frac{c_0}{2L}, \tag{1}$$

where  $c_0$  is the acoustic velocity of the fluid that fills the cavity and  $L$  is the cavity length. The quality factor of the cavity system is the resonant frequency  $f$  divided by the half-power bandwidth  $W$  or linewidth of the resonance curve (Figure 2):

$$Q = \frac{f}{W} . \tag{2}$$

The resonant frequency and linewidth are found by fitting a Lorentzian curve (Mehl, 1978; Migliori & Sarrao, 1997) to the measured amplitude spectrum. When a rock sample is introduced, the resonant frequency either increases or decreases depending primarily on the velocity and density properties of the sample and its location in the cavity. Similarly, the quality factor changes to reflect primarily the attenuation properties of the sample.

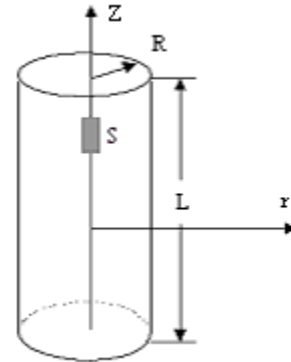


Figure 1: A cylindrical cavity with a small sample of rock inside.

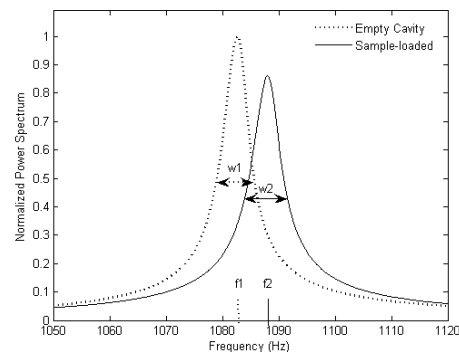


Figure 2: DARS resonance curves.  $f_1$  is the resonant frequency without the sample and  $W_1$  is the half-power bandwidth.  $f_2$  and  $W_2$  are the frequency and linewidth with the sample.

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### The DARS Measurement

A block diagram of the DARS setup is shown in Figure 3. The key component is the cylindrical cavity, which is immersed in a tank filled with fluid. Piezoceramic sources are used to excite the fluid resonance. A high sensitivity hydrophone is embedded in the wall of the cavity to detect acoustic pressure. The sample is moved vertically along the axis of the cavity to test various domains of pressure and flow. A computer-controlled stepper motor provides accurate and repeatable positioning of the sample. A lock-in amplifier is used to scan the frequency, and record a selected resonance curve in typical frequency steps of 0.1 Hz. Sample movement and data acquisition is automated and controlled by computer. Typical measurement results are shown in Figure 2. The resonance frequency and linewidth are extracted to give the results (first mode) shown in Figures 4 and 5 for samples at different locations in the cavity. The unperturbed background field in the cavity is a standing wave with a pressure anti-node at cavity's center and velocity antinodes near the ends. At the center, the effects of acoustic pressure dominate and the smaller compressibility of the sample shifts the frequency higher than the empty value (Figure 4). At the ends of the cavity, the effects of acoustic velocity dominate and the higher density of the sample causes the frequency to shift lower. There are two points (first mode) within the cavity where the compressibility and density contributions exactly cancel and the resonant frequency is identical to that of the empty cavity. The linewidth  $W$  (Figure 5) exhibits similar behavior with changing sample position.

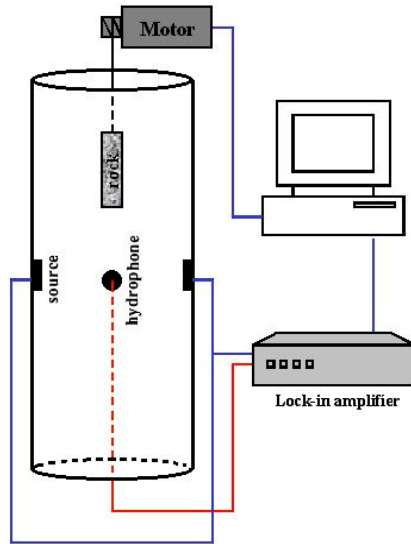


Figure 3: The DARS setup includes computer controlled sample positioning and swept frequency (phase lock) data acquisition.

### Attenuation Results

The early test of DARS included several nonporous samples and four common rock samples (See sample picture in Figure 6). There are two different samples of Berea sandstone, one of Boise sandstone, and one of chalk. Their properties are listed in Table 1. We also tested nonporous samples made from aluminum, various plastics, Lucite, brass, and rubber. Thirty synthetic samples with a variety of pseudo-permeability and pseudo-porosity combinations were studied also. The pore space and permeability of the synthetic samples range from 8 to 27% and from 250 to 1500 mDarcy. Both the real rocks and synthetic samples were fully saturated with the same fluid contained in the cavity. Furthermore, we conducted all measurements at temperature of  $22 \pm 0.2^\circ\text{C}$  and considered only the first resonance mode.

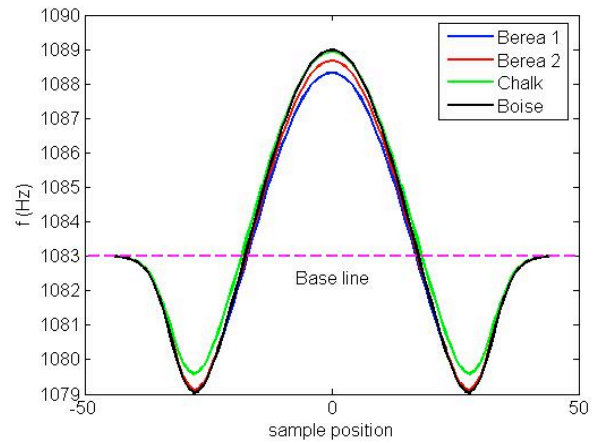


Figure 4: Variations of resonant frequency with sample location for four porous samples. The baseline corresponds to the empty cavity.

We present here results for the four rock samples only. Cross-plots of measured resonance frequency  $f$  and linewidth  $W$  are shown in Figure 7 for varying position of the sample within the cavity. The common point marked “empty cavity” corresponds to the sample far outside the cavity. The point marked the “x” corresponds to the middle of the cavity. Remember that the ratio of frequency to linewidth is the system quality factor. The data shown in Figure 7 correspond to varying (slightly) system  $Q$  with sample position but show distinct differences and easily separated values for the four samples. The slight variations are easily seen in Figure 8, where system  $Q$  is plotted versus frequency, a surrogate for sample position. The

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variation (e.g., change in slope) in system  $Q$  reflects the different attenuation properties of the sample.

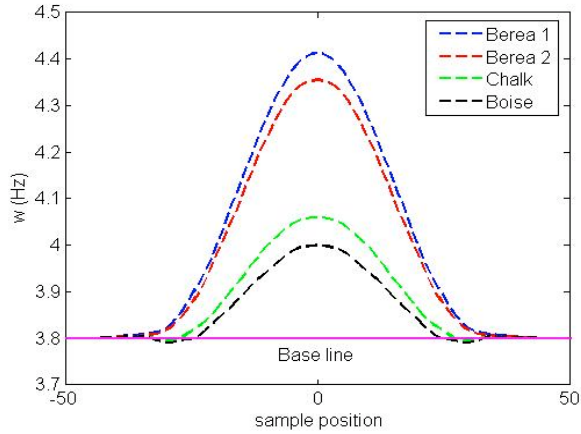


Figure 5: Variations of resonance linewidth with sample location for four porous samples. The baseline corresponds to the empty cavity.



Figure 6: Four rock samples (1 Boise sandstone, 1 chalk, and 2 Berea sandstones) used in this DARS experiment.

Rock type	$\rho$ (g/cc)	$\phi$ (%)	$k$ (mDarcy)
Boise	2.32	12	1.0
Chalk	1.79	34	2.2
Berea 1	2.10	19	127
Berea 2	1.85	22	368

Table 1: Properties of four rock samples used in this DARS experiment.

We compared the  $Q$  values at cavity's midpoint (compressive  $Q$ ) with the measured flow and storage properties, i.e., permeability and porosity, for the four

samples (Figure 9). We see a monotonically decreasing value of  $Q$  with increasing permeability that changes over three orders of magnitude. In Figure 10, we see a similar behavior of  $Q$  with porosity except for the distinct outlier for the high porosity but low permeability Chalk sample. These results strongly suggest that DARS " $Q$ " may be used to qualitatively interpret permeability in porous media.

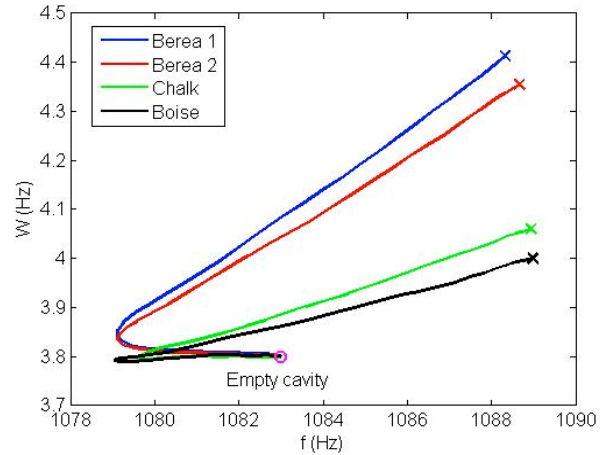


Figure 7: Cross-plot of resonance frequency and half-power linewidth ( $W-f$ ) for four different rocks. The traces correspond to sample position. "x" marks the middle of the cavity, i.e., the pressure antinode, and "o" is a point far outside the cavity, i.e., "empty cavity."

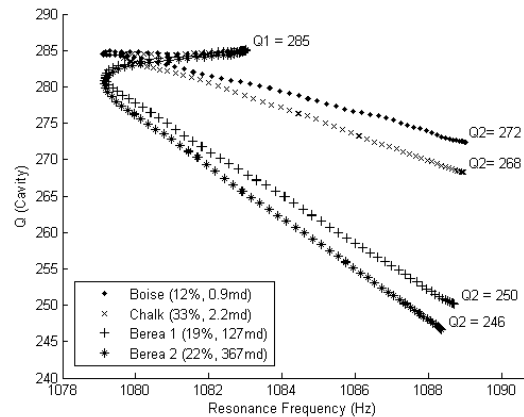


Figure 8: Cavity resonance frequency vs. quality factor for four different porous samples.  $Q_1 = 285$  is the quality factor of the empty cavity.  $Q_2$  is the quality factor for a sample at the center of the cavity.

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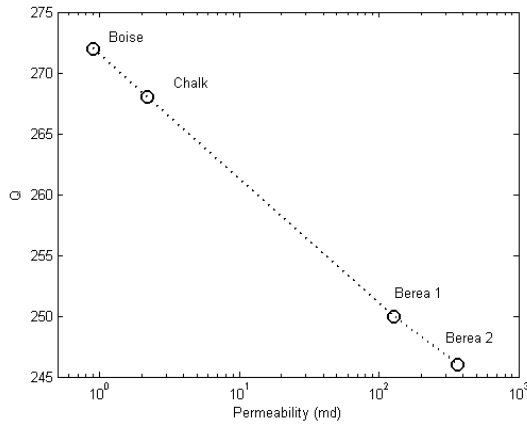


Figure 9: The quality factor corresponding to the four rock samples as a function of permeability. Permeability is measured with a conventional flow method.

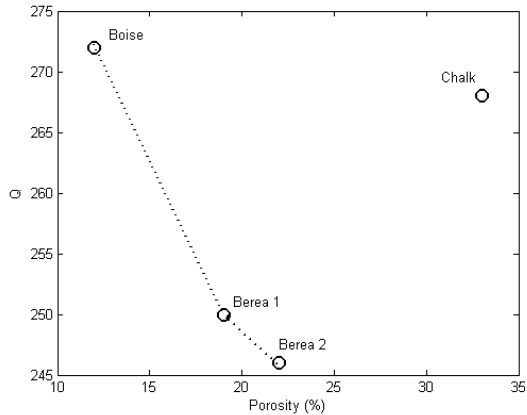


Figure 10: The quality factor corresponding to the four rock samples as a function of porosity.

the high-resolution field seismic. The experimental results showed that both permeability and porosity have considerable effects on the “compressive” attenuation property of a porous sample. The “system  $Q$ ” discussed in this paper is the quality factor of cavity with a sample inside. We are currently working on the quantitative conversion from this system  $Q$  to a value for sample  $Q$ .

References

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Conclusion

We have conducted laboratory measurements of attenuation on both synthetic rocks and real rock samples. These observations were made possible with the use of our newly developed Differential Acoustic Resonance Spectroscopy (DARS) system. The DARS technique operates on the principle of perturbation of a cavity resonance with the introduction of an acoustically small sample of rock or other material. By analyzing the change in the cavity’s normal modes, we can estimate the acoustic properties of the sample. Rock samples were measured using DARS at near 1 kHz, a frequency that is close to borehole logging

## EDITED REFERENCES

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