Improved materials characterization by pressure-dependent ultrasonic attenuation in air-filled permeable solids

Peter B. Nagy
Aerospace Engineering and Engineering Mechanics Department, University of Cincinnati, Cincinnati, Ohio 45221-0070

David Linton Johnson
Schlumberger-Doll Research Center, Ridgefield, Connecticut 06877-4108

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Recently developed airborne ultrasonic inspection techniques can supplement other methods routinely used for materials characterization of permeable solids. In particular, the velocity and attenuation of the slow compressional wave transmitted through thin plates of a few millimeter thickness can be used to assess the tortuosity and dynamic permeability of the specimen. The main advantage of the ultrasonic method over conventional flow resistivity, electrical conductivity, and other measurements is that it can be used to study the heterogeneity of the pore structure at scales comparable to the grain size. In the 100–500 kHz frequency range slow wave images can be obtained with resolution on the order of 1 mm or better. However, due to substantial viscous and scattering losses, the sensitivity of the method is relatively low therefore, the technique is limited to materials of at least 10% connected porosity and permeability higher than 200 mD. It is demonstrated in this letter that varying the air pressure significantly enhances the capabilities of slow wave inspection. Using high-pressure air saturation significantly reduces the absorption losses so that better resolution can be achieved by increasing the frequency. Alternatively, materials of lower permeability or specimens of higher thickness can be inspected at the same frequency. In addition, scattering losses can be eliminated by subtracting images taken at the same frequency but at different pressures. © *1996 American Institute of Physics.* [S0003-6951(96)00526-8]

On the scale of hundreds of grains, the average macroscopic properties of permeable rocks can be most easily assessed by static or quasistatic methods such as flow resistivity or electrical conductance measurements on standard specimens of a few inches in dimensions. However, the degree of disorder on the scale of a couple of grains is also of crucial importance in characterizing the material. Such small-scale variations of the permeability due to inhomogeneity and anisotropy of the pore structure are much more difficult to measure by conventional techniques. One obvious way of concentrating the fluid flow to a small area of the specimen is to use high-frequency dynamic measurements in the ultrasonic range where the acoustic wavelength is small enough to assure the required inspection resolution. For this purpose, we previously introduced an experimental technique based on the transmission of airborne ultrasonic waves through air-filled permeable plates between 10 and 500 kHz.[1,2] Based on this method, a high-resolution slow wave imaging system was developed to study the inhomogeneous pore structure in permeable formations.[3,4]

First, the velocity and attenuation coefficient of the slow compressional wave through thin slabs of air-filled specimens were studied as functions of frequency in porous ceramics of 2–70 D and natural rocks of 200–700 mD permeability.[2] In the low-frequency (diffuse) regime, the experimental results were in good agreement with theoretical predictions. Here, the phase velocity and attenuation coefficient are determined by the permeability of the specimen and both increase proportionally to the square-root of frequency. In the high-frequency (propagating) regime, the experimental results agreed with the theoretical predictions for the phase velocity but not for the attenuation coefficient. Here, the phase velocity asymptotically approaches a maximum value determined by the tortuosity of the specimen while the attenuation coefficient apparently becomes linearly proportional to frequency instead of the expected square-root relationship. More recently, Leclaire *et al.* also found a similar excess attenuation in a very high porosity (98%) air-filled absorbent above 300 kHz.[5]

A point-by-point analysis of the transmitted field through coarse-grain specimens at different frequencies revealed a significant variance in both insertion loss and delay, which suggested the presence of strong incoherent components in the transmitted field.[4] In all coarse-grain specimens, a readily perceivable incoherent component was found. The uneveness of the total transmitted field is primarily due to the presence of highly transparent and strongly attenuating regions instead of random interference caused by strong incoherent waves. This observation leads to the basic idea of using slow waves to map the local permeability distribution in heterogeneous permeable solids. Certain natural rocks exhibit quite even distribution on this scale while others show low permeability, tightly packed layers or high permeability, loose layers, and cracks.[3] There is a perceivable scattering noise on most pictures, which is an artifact caused by the dynamic nature of the ultrasonic ''permeability'' measurement. At low frequencies, the scattering noise does not significantly interfere with the mapping of the permeability distribution. However, the scattering noise limits our ability to increase the imaging resolution by raising the inspection frequency. In this letter, we will show that this adverse scattering noise can be significantly reduced by exploiting the pressure dependence of the slow wave attenuation in air-filled permeable solids.

The total attenuation of slow waves through air-filled permeable solids can be attributed to absorption and scattering effects. The absorption loss is mainly due to viscous friction and partly to thermal effects. Generally, the viscous loss is an unknown function α_{viscous} of the pore size a_{pore} as measured by the viscous skin depth δ. Similarly, the usually lower thermal loss is an unknown function α_{thermal} of the pore size as measured by the relevant yardstick, i.e., the diffusion length d in the gas. In most cases discussed in the open literature, the inspection frequency is chosen to be low enough (below 5 kHz) to neglect scattering losses. However, in pursuit of better lateral imaging resolution, we increased the inspection frequency well above the scattering limit therefore we have to either eliminate or account for the additional losses in our measurements. The scattering loss is another unknown function $\alpha_{\text{scattering}}$ of the pore size as measured by the relevant yardstick, i.e., the acoustic wavelength λ in the gas. The viscous skin depth, diffusion length, and acoustic wavelength are $\delta=\sqrt{\mu/(\rho\pi f)}$, $d=\sqrt{\chi/(\rho c_p \pi f)}$, and $\lambda=c/f$, respectively. Here, f denotes the frequency, χ is the thermal conductivity, and c_p is the specific heat at constant pressure. From all the parameters involved, the density of the gas ρ is the only one that depends on pressure p according to $\rho=p/(RT)$, where $R=289$ J/kg K is the universal gas constant divided by the average molecular weight of air. It is well known that the viscosity μ, thermal conductivity χ, and sound velocity c of gases are independent of pressure and are functions of temperature T only.[6]

The viscous skin depth and diffusion length are strongly pressure dependent because they are inversely proportional to the square-root of density. In comparison, since the bulk modulus of air increases with pressure in the same way as its density, the acoustic wavelength is independent of pressure. As a result, absorption losses are also pressure dependent while scattering losses are not. Although the pressure dependence of the absorption loss is not generally known, certain assumptions can be made. In a wide range of applications, both the low- and high-frequency absorption coefficients are proportional to the square-root of the kinematic viscosity $\eta=\mu/\rho$ of the gas,[7–12] i.e., the attenuation is expected to be inversely proportional to the square-root of pressure. The pressure dependence of the total attenuation is then of the form $\alpha_{\text{total}}=\alpha_a p^n+\alpha_s$, where α_a is the absorption loss at unit pressure, α_s is the constant scattering loss, and the power n is close to -0.5.

In order to study the pressure dependence of slow-wave propagation in air-filled permeable solids we used our previous developed experimental system,[2] but placed the ultrasonic transducers and the specimen in a vacuum chamber that allowed us to decrease the ambient pressure. As we expected, there was no appreciable change in the slow wave velocity. In comparison with the velocity, the attenuation was found to be very sensitive to air pressure. Figure 1 shows the slow wave attenuation coefficient as a function of air pressure for four different grades of air-filled porous glass specimens at 350 kHz. Symbols are experimental data and the solid lines are best-fitting polynomials of the form of $\alpha(p)=\alpha_s+\alpha_a p^{-1/2}$.

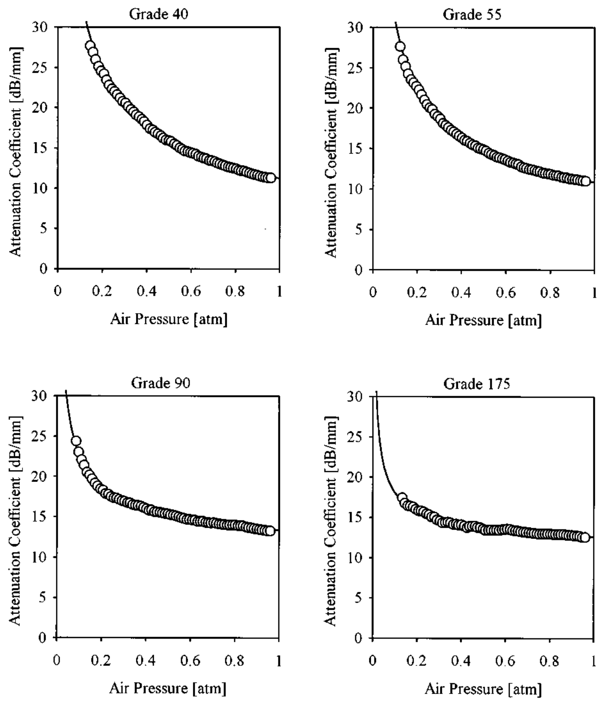

FIG. 1. Slow wave attenuation coefficient as a function of air pressure for four different grades of air-filled cemented glass bead specimens at 350 kHz. Symbols are experimental data and the solid lines are best fitting polynomials of the form $\alpha(p)=\alpha_s+\alpha_a p^{-1/2}$.

The α_a and α_s coefficients of the best-fitting polynomial can be regarded as the experimentally determined absorption coefficient at atmospheric pressure and pressure-independent scattering coefficient, respectively. Figure 2(a) shows the total attenuation coefficient and its absorption component for the same four grades of air-filled porous glass specimens as determined from the best-fitting polynomial. The theoretical absorption coefficients were taken from an earlier study.[2] Previously, we had to rely on the measured total attenuation coefficient which correlated very poorly with the theoretical absorption coefficient calculated from the permeability of the material. Clearly, the absorption coefficient as determined from the pressure-dependent component of the measured total attenuation correlates much better with the theoretical prediction. We can conclude that, in coarse-grain materials, only the thereby determined absorption coefficient can be regarded as a reliable measure of dynamic permeability. The significant excess attenuation observed in the two largest grades appears to mainly be due to scattering as indicated by the weak pressure dependence of the total loss. Figure 2(b) shows the scattering coefficient as a function of the interstitial pore size. As expected, the scattering coefficient greatly increases with grain size, but more quantitative analytical predictions are currently not available for comparison with our experimental data.

For slow wave propagation, an ideal saturating fluid should really have physical properties somewhere between those of water and air so that the viscous losses would be low, but the fluid motion still would not cause significant vibrations in the frame. Although there is not such natural fluid, ordinary high-pressure air combines the best of both worlds. It is expected that the permeability threshold of the

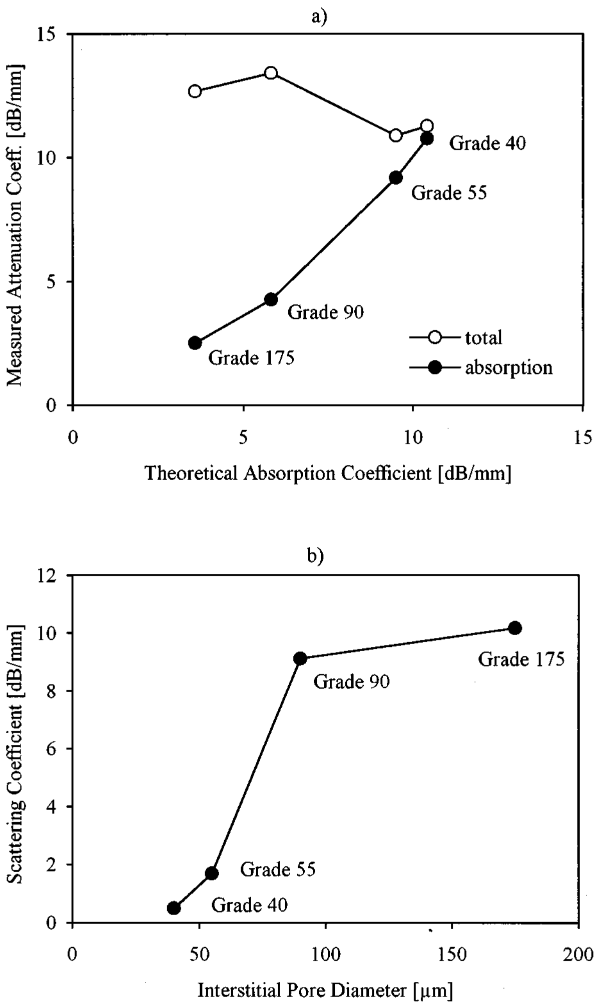

FIG. 2. Measured (a) absorption, α_a, and (b) scattering, α_s, coefficient for four different grades of air-filled cemented glass bead specimens at 350 kHz.

slow wave inspection technique could be lowered to ~10–20 mD simply by taking the slow wave images at elevated pressures.

The current slow wave imaging technique requires further improvement in two major areas. First, at the high inspection frequencies required to achieve desirable resolutions, acoustic scattering superimposes on and partially overshadows the viscous losses we would like to map. Second, because of the very high attenuation of the slow wave in natural rocks, we must use very thin slices of 1–2 mm in thickness, which are not only fragile but also represent only a couple of grains instead of the optimum thickness of 10–20 times the average grain size. Controlling the air pressure can solve, or at least significantly mitigate, both problems. We already demonstrated that changing the pressure can be used to separate viscous losses from scattering. Slow wave images taken at different pressures but at the same frequency can be simply subtracted from each other to obtain an image free of scattering interference. In addition, by placing the imaging probe with the specimen in a pressure vessel containing compressed air, we can drastically reduce the viscous losses. In this way, specimens of much lower permeability or much larger thickness can be inspected, whichever is needed more to expand the feasibility of the method in a practical situation.

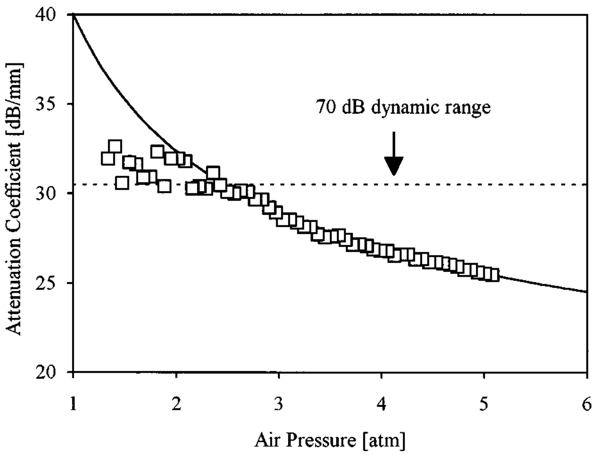

FIG. 3. Measured slow wave attenuation coefficient through a 2-mm-thick Berea sandstone of 200 mD permeability at 350 kHz.

We can demonstrate the feasibility of enhanced slow wave inspection based on high-pressure air saturation by a simple transmission measurement through a highly attenuating specimen. Figure 3 shows the measured slow wave attenuation coefficient through a 2-mm-thick Berea sandstone of 200 mD permeability at 350 kHz. This is a relativity low permeability specimen which could not be inspected above 150–200 kHz by our previous technique at atmospheric pressure since the insertion loss exceeded the 70 dB dynamic range of our system. The slow wave attenuation in such low-permeability materials is dominated by viscous absorption which greatly decreases with increasing pressure. Above ~3 at, the insertion loss drops the into acceptable dynamic range and we can measure the slow wave attenuation coefficient in spite of the relatively high inspection frequency. In such low-permeability materials, the slow compressional wave cannot be detected at this frequency without raising the air pressure.

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