

COHERENT AND INCOHERENT SCATTERING MECHANISMS IN AIR-FILLED PERMEABLE MATERIALS

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INTRODUCTION

Ultrasonic evaluation of porous materials can take advantage of some very specific acoustic phenomena that occur only in fluid-saturated consolidated solids of continuously connected pore structure. The most interesting feature of acoustic wave propagation in such media is the appearance of a second compressional wave, the so-called slow wave [1,2]. The slow compressional wave represents a relative motion between the fluid and the solid frame. This motion is very sensitive to the kinematic viscosity of the fluid and the dynamic permeability of the porous formation. Certain material properties such as tortuosity, permeability, porosity, and pore size, shape and surface quality are inherently connected to the porous nature of the material and can be evaluated best from the propagation properties of the slow compressional wave.

Due to the relatively high kinematic viscosity of air, the slow compressional wave is even more attenuated in air-filled porous samples than in water-saturated ones, but it is the only mode which is generated with a significant amplitude, therefore its detection is fairly simple [3]. Even a very weak slow wave, attenuated by as much as 50-60 dB can be easily detected due to the lack of stronger background signals caused by the direct arrivals and scattered components of the fast compressional and/or shear waves. In order to exploit these unique features, we have recently developed a slow wave inspection technique based on the transmission of airborne ultrasonic waves through air-filled porous plates [4]. This technique can be readily used to study the frequency-dependent velocity and attenuation of the slow compressional wave in different porous materials including natural rocks in both low-frequency (diffuse) and high-frequency (propagating) regimes. In the diffuse region, which is usually below 100 kHz, both the velocity and the attenuation coefficient are primarily determined by the static permeability of the material. In the propagating region, the velocity depends on the tortuosity only while the attenuation coefficient is predicted to decrease with increasing permeability. Generally, the experimentally observed propagation parameters are consistent with existing theoretical models [5-8] except for an anomalous excess attenuation at very high frequencies. The excess high-frequency attenuation could

be additional absorption due to increased viscous friction caused by the irregularity of the pore channels or geometrical scattering due to phase cancellation between rays propagating through various channels depending of the material properties [4]. For example, the existence of a wide pore size distribution can easily result in as much as 100 % increase in the viscous losses [9].

The average permeability over a large cross section is most easily estimated from static or low-frequency dynamic flow resistivity measurements. In comparison, high-frequency acoustic measurements can be used to study the local variations of the dynamic permeability with fine resolution on the order of 1 mm by using focused ultrasonic beams. It is expected that the spatial variation of the local high-frequency attenuation contains valuable additional information on the heterogeneity of the pore space. However, it is of great importance to understand the underlying physical process which causes the observed loss. If the local variation is primarily caused by geometrical scattering, i.e., phase cancellation between the signals transmitted through pores of different tortuosity, then the high-frequency attenuation distribution is essentially an artifact caused by the dynamic nature of the method that was necessary to localize the measurement and it cannot be directly related to the local permeability to be determined. However, if the local variation is primarily caused by viscous absorption, then the high-frequency attenuation is a useful measure of the sought local permeability. The main goal of this paper is to identify the attenuation mechanism responsible for the significant local variations observed in the high-frequency transmission distribution of air-born ultrasonic waves through permeable solid plates.

HIGH-FREQUENCY ATTENUATION

Recent experimental results by the author indicated that the attenuation coefficient of the slow compressional wave in air-filled porous solids always approaches a more or less linear slope at high frequencies [4]. This slope is determined by the irregularity of the pore shape and the degree of geometrical disorder in the material, but essentially independent of pore size. In order to further investigate whether the observed high-frequency attenuation is dominated by viscous or geometrical scattering losses, we have introduced a novel experimental technique based on the point-by-point measurement of the slow wave transmission through permeable solids. Probably the most basic difference between viscous absorption and geometrical scattering is exhibited through their substantially different effect on the total acoustic energy carried by the slow compressional field. Viscous losses directly reduce the total acoustic energy by dissipation into heat. On the other hand, elastic or geometrical scattering simply converts the well-collimated coherent acoustic wave into diffusely propagating incoherent wave without reducing the total acoustic energy. Because of this fundamental difference between viscous and geometrical scattering, the two mechanisms can be best differentiated from the energy balance of the total acoustic field. Unfortunately, ordinary phase-sensitive acoustic sensors are rather difficult to use for energy measurements since their output is proportional to the average field over their finite aperture. This makes them ideal to measure the transmitted (or reflected) coherent component of the total field when the receiving aperture is large with respect to the acoustic wavelength, but not for the incoherent components. Generally, the total acoustic field $u = u(x, y, z)$ can be written as $u = u_c + u_i$, where the coherent component is simply the ensemble average of the field $u_c = \langle u \rangle$ for a large number of statistically identical representations of the randomly inhomogeneous medium. For practical purposes, the ensemble average is often substituted by the spatial average of the field for a large area covering the whole inhomogeneous specimen. The incoherent field

can be determined as the deviation of the total field from the average field, i.e., $u_i = u - \langle u \rangle$. Of course, the total acoustic intensity can be also written as the sum of the coherent and incoherent contributions $\langle u^2 \rangle = \langle u_c^2 \rangle + \langle u_i^2 \rangle$. In our previous insertion loss experiments [4], we actually measured only the coherent transmitted signal, $u_{c,t}$. Using a very small "point" sensor to map the field distribution just behind the porous plate, we could also measure the total transmitted field, $u_t = u_{c,t} + u_{i,t}$. Unfortunately, such a point sensor is technically very difficult to construct. Using a sharply focused detector, we can measure a combination of the coherent and incoherent field, $u_{c,t} + v$, where v is a low-pass filtered or smoothed representation of the incoherent transmitted acoustic field $u_{i,t}$ depending on the effective aperture of the receiver relative to the lateral coherence length of the incoherent field.

Naturally, in the case of dominantly viscous losses the total field is attenuated almost as much as the coherent component since the missing acoustic energy is dissipated into heat. Even in this case however, there will be a perceivable incoherent field because of the unevenness of the transmitted field caused by the inhomogeneity of the material, but the incoherent transmission will be of the same order of magnitude, i.e., within a few dB of the coherent transmission. This is why we use the term of viscous scattering when a significant, but not dominating, incoherent component is generated by excess viscous drag in the irregular pore channels. Of course, in the case of a completely homogeneous viscous medium (e.g., a rubber plate) the missing coherent energy is fully converted into heat and there is no incoherent scattering at all.

EXPERIMENTAL SYSTEM AND RESULTS

The experimental system is shown in Figure 1. Essentially the same standard ultrasonic NDE equipment was used as in our previous experiments [3,4] In order to determine whether the missing energy of the coherent transmission indicated by the observed attenuation is primarily viscous loss or rather incoherent geometrical scattering, we had to make certain modifications on our original experimental system that used large-

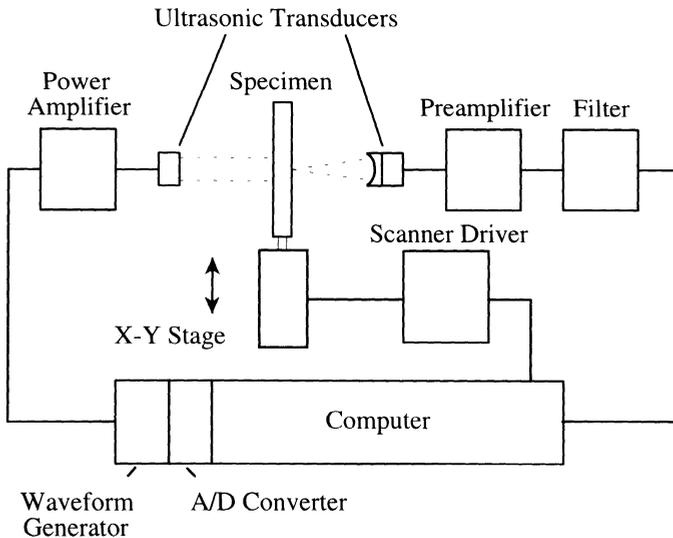


Figure 1 Block diagram of the modified experimental system.

aperture unfocused transducers and measured only the coherent transmission.. The most important difference is that the receiver was equipped with a 1"-focal-length Plexiglas lens which assures a small receiving aperture of approximately 1 mm in diameter at 250 kHz. In this way, we can map the distribution of the total transmitted field without significantly blurring the local deviations from the average wave. The specimen is mounted on a computer controlled translation stage for automated scanning.

Figure 2 shows the point-by-point insertion loss and insertion delay distribution through a 3.2-mm-thick cemented glass bead specimen of Grade 175 at 250 kHz at 250 different locations along a 2"-long straight line. This was our highest-permeability specimen which was supposed to have the lowest viscous drag and therefore the lowest slow wave absorption. This particular specimen was used in this part of the study because, although all other inspected specimens showed evidence of anomalous excess attenuation

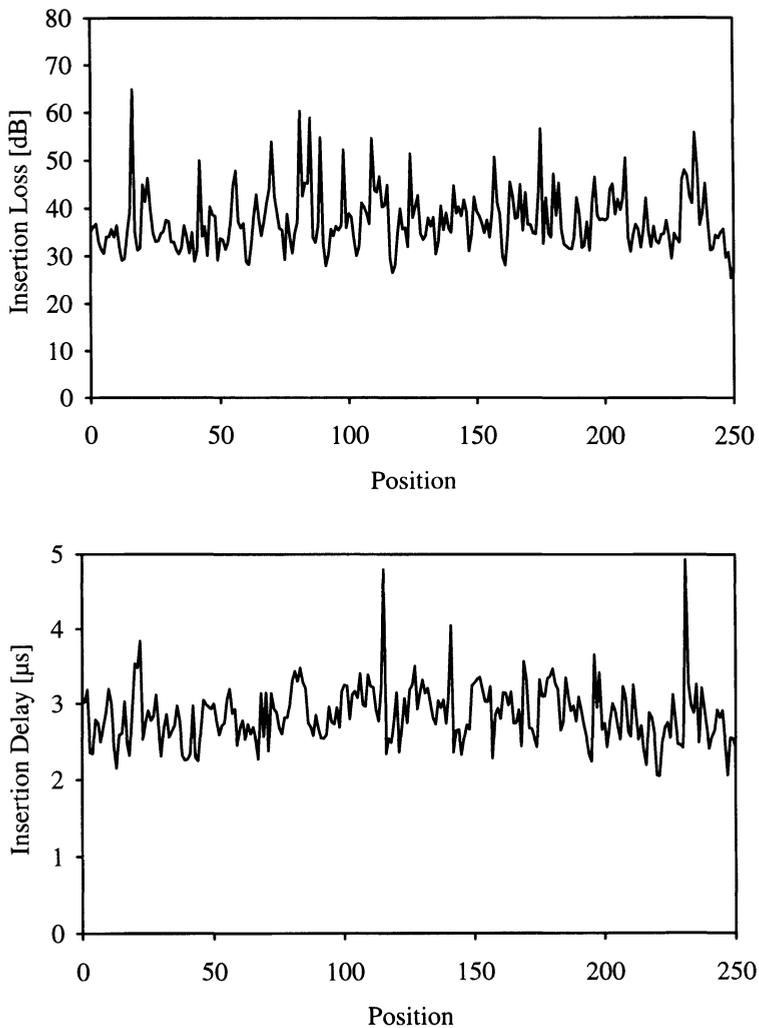


Figure 2 Point-by-point insertion loss and insertion delay distribution through a 3.2-mm-thick cemented glass bead specimen of Grade 175 at 250 kHz.

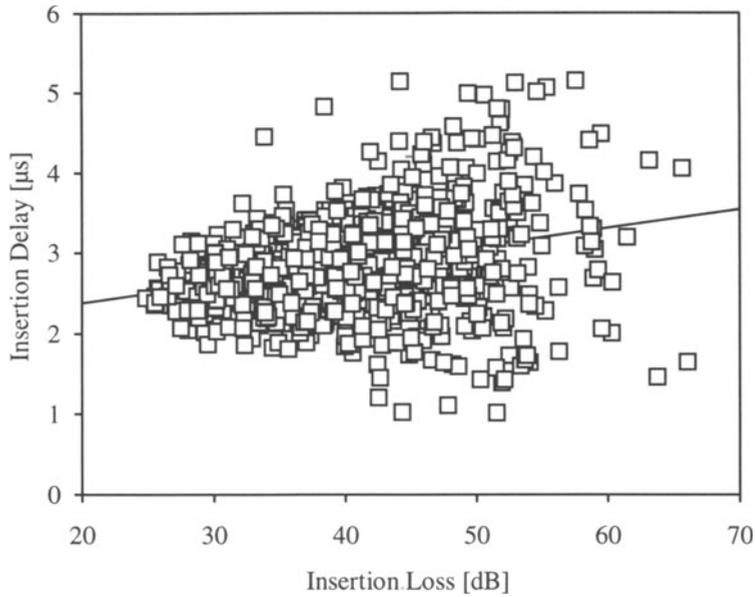


Figure 3 Cross-correlation between the insertion loss and insertion time distributions.

at high frequencies, this sample exhibited by far the strongest effect. According to the significant variance of the data shown in Figure 2, both insertion loss and delay reveal the presence of strong incoherent components in the transmitted field. Figure 3 shows the cross-correlation between the insertion loss and insertion time distributions. The insertion loss and delay are obviously not entirely independent of each other in a statistical sense. As one would expect, propagation along longer, more tortuous pore channels is more attenuated, but the correlation is not very strong.

From the point-by-point insertion loss and insertion delay data accumulated over a 2" x 2" area of the 3.2-mm-thick cemented glass bead specimen of Grade 175 at 250 kHz, the coherent and incoherent transmissions are $u_{c,t}^2 = -38.9$ dB and $\langle u_{i,t}^2 \rangle = -38.5$ dB, respectively, relative to the incident wave. In other words, there is a perceivable incoherent component, but not significantly stronger than the coherent one, even when considering the possible underestimation in the transmitted incoherent field due to the finite size of the receiving aperture. If geometrical scattering dominated the observed attenuation the field would be strong but very irregular behind the plate. These measurements illustrate that the field becomes generally very weak behind the plate, which suggests that the attenuation is dominantly due to viscous losses.

The same general conclusion can be drawn also from a number of other observations. Another way to differentiate between viscous and geometrical scattering is by considering the frequency-dependence of the total field at any particular point. In the case of viscous absorption, a darker-than-average point remains darker-than-average at all frequencies as the signal becomes progressively weaker with increasing frequency. In comparison, in the case of geometrical scattering, a dark spot is generally due to destructive interference between otherwise strong incoherent components. The same spot often becomes brighter at higher frequencies, a clear sign of dominantly incoherent transmission,

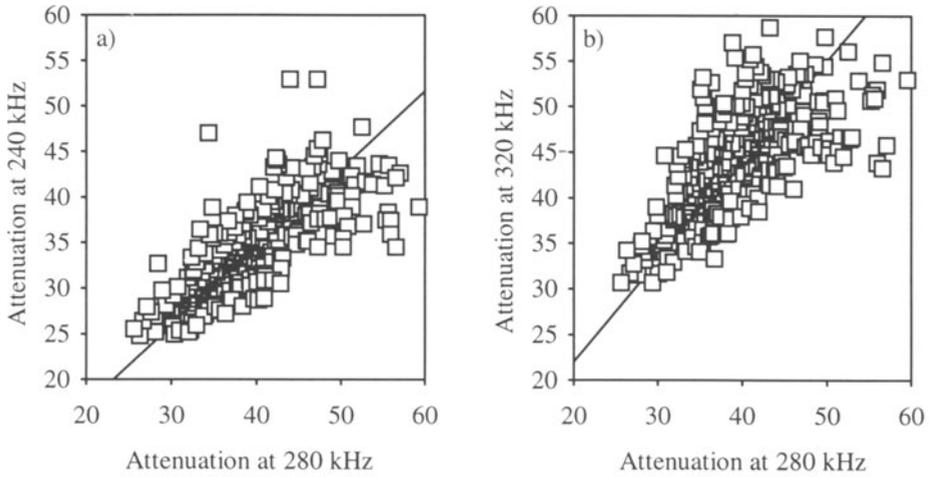


Figure 4 Point-by-point comparison between the measured insertion loss at 240, 280, and 320 kHz in the same cemented glass bead plate.

which cannot happen in the case of viscous scattering. Figure 4a shows the point-by-point comparison between the measured insertion losses at 280 kHz and a significantly lower frequency of 240 kHz in the same cemented glass bead plate. In a similar way, Figure 4b shows the correlation between the insertion losses measured at 280 kHz and 320 kHz. There is a generally strong but less than perfect correlation between the measured losses at different frequencies. From the linear frequency-dependence of the coherent attenuation, the insertion loss is expected to be 16.7% lower at 240 kHz than at 280 kHz. The point-by-point statistical analysis indicated a difference of $16.2\% \pm 1.4\%$. Similarly, the insertion loss is expected to be 14.3% higher at 320 kHz than at 280 kHz. The point-by-point statistical analysis indicated a difference of $12 \pm 2\%$. In other words, the unevenness 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 also indicates that the observed excess attenuation is primarily due to viscous scattering with clear evidence of some geometrical scattering.

SLOW-WAVE IMAGING

The same effect can be observed on the two-dimensional maps of the transmitted acoustic wave shown in Figure 5 for two different frequencies. Both pictures were taken from the same 2" x 1.4" area. Since the average attenuation increases from less than 40 dB at 290 kHz to more than 50 dB at 380 kHz, both picture was normalized to the average loss at that particular frequency. The total dynamic range of the pictures from black to white was limited to 30 dB with 16 gray levels. There is an apparent increase in both contrast and resolution with increasing frequency, but a detailed comparison reveals that areas of darker or brighter intensity remain respectively darker and brighter at all frequencies.

These pictures well illustrate that, in spite of the presence of some incoherent components caused by elastic and geometrical scattering, the dominating loss mechanism is viscous absorption. This result indicates that transmission of air-born ultrasonic waves through thin plates of permeable solids can be readily used to build a high-sensitivity, high-resolution slow wave imaging device to study the heterogeneous pore structure with mm-

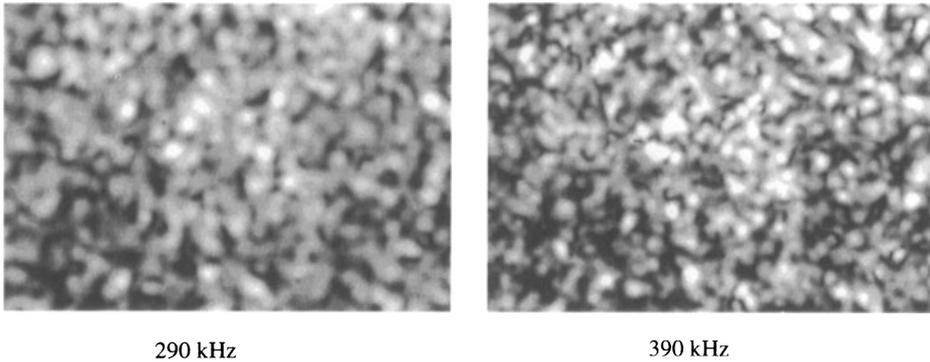


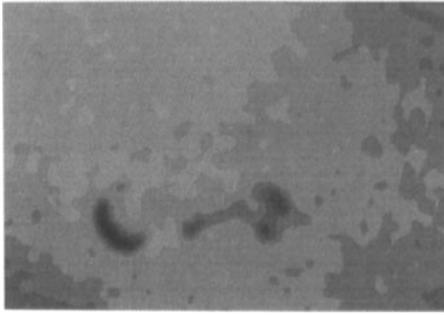
Figure 5 Transmission images of a 3.2-mm-thick, 2" x 1.4" Grade 175 glass plate at two different frequencies.

range resolution. It was recently demonstrated that such slow wave transmission images of porous natural reservoir rocks reveal some unique information previously unavailable by conventional inspection techniques [10]. Currently, the threshold sensitivity of our system is approximately 100 mD and the spatial resolution is between 0.5 and 2.5 mm in the 100 kHz to 500 kHz frequency range. Recent experimental results by Prince et al. indicated that permeability in sandstones with permeability above 10 mD is dominated by mm-sized microcircuits, that is features within the resolution range of the suggested slow wave imaging method [11]. Slow wave imaging can show the aspects of the porosity which actually contribute to the transport of fluid in the rock, ignoring dead ends and channels not properly oriented to the flow field, therefore it offers an interesting alternative to existing imaging methods.

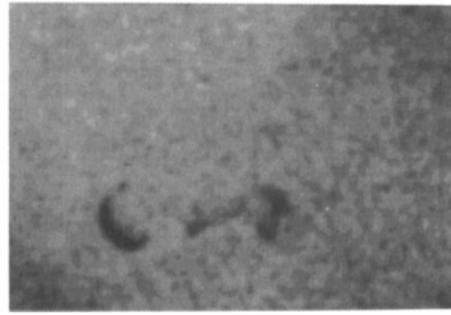
As an example, Figure 6 shows the slow wave images of a 1.8-mm-thick Grade 10 sintered bronze filter at two different frequencies. In order to further increase our lateral resolution, we equipped the transmitting transducer with a similar Plexiglas lens used on the receiving transducer (see Figure 1). Both pictures have a 30 dB dynamic range divided into 16 gray levels. The average attenuation increases from 34 dB at 290 kHz to 50 dB at 450 kHz. The permeability appears to slightly decrease towards the right side of the specimen, which is most probably due to pressure or temperature differences during sintering. There are also some dark spots well visible especially on the higher resolution 450 kHz picture, which were identified as localized corrosion spots of the metal caused by chemical contamination.

CONCLUSIONS

Transmission of airborne ultrasonic waves through thin air-filled porous plates was used to study slow wave propagation in permeable solids. The main goal of this paper was to study the local variation of the high-frequency attenuation through heterogeneous formations. The physical origin of the observed high-frequency attenuation could not be established from our previous experiments based on the measurement of the coherent transmission only. In order to separate the effect of elastic scattering from that of viscous absorption, we modified our system so that both incoherent and coherent components of the transmitted acoustic wave could be measured separately by a sharply focused receiver. Our experimental results indicated that the loss of the coherent transmission was



290 kHz



450 kHz

Figure 6 Slow wave images of a 1.8-mm-thick, 2" x 1.4" Grade 10 sintered bronze filter at two different frequencies.

significantly larger than the accompanying increase in the incoherent field. The experimentally observed strong spatial variation of the attenuation is mainly due to viscous effects.

We have introduced numerous technical modifications and improvements such as beam focusing, automated scanning, increased dynamic range, and greatly accelerated data acquisition to facilitate localized transmission measurements. An important spin-off of this effort is the development of a new slow wave imaging concept that could be used to study the heterogeneous pore structure in permeable solids. It is expected that this new imaging technique can complement such methods as hydrodynamic dispersion measurements, confocal laser microscopy, and petrography for characterizing flow channels in porous materials.

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