Observation of a new surface mode on a fluid-saturated permeable solid

Peter B. Nagy

The Ohio State University, Columbus, Ohio 43210

(Received 24 January 1992; accepted for publication 6 April 1992)

Almost ten years ago, S. Feng and D. L. Johnson predicted the presence of a new surface mode on a fluid/fluid-saturated porous solid interface with closed surface pores [J. Acoust. Soc. Am. 74, 906 (1983)]. We found that, due to surface tension, practically closed-pore boundary conditions can prevail at an interface between a nonwetting fluid (e.g., air) and a porous solid saturated with a wetting fluid (e.g., water or alcohol). Surface wave velocity and attenuation measurements were made on alcohol-saturated porous sintered glass at 100 kHz. The experimental results show clear evidence of the new "slow" surface mode predicted by Feng and Johnson.

The analytical method of Feng and Johnson can be easily applied to a surface wave propagating along the "free" (air-loaded) surface of a fluid-saturated rock. In the ideal case of completely closed surface pores and viscosity-free fluid, two types of surface wave can propagate: there is a pseudo-Rayleigh mode, which leaks its energy into the slow compressional wave, and a true surface mode with velocity slightly below that of the slow wave. The second mode is a simple form of the new interface mode predicted by Feng and Johnson when the superstrate fluid is extremely rare and highly compressible like air. Theoretically, the slow interface mode becomes slightly leaky, too, since its velocity is higher than the sound velocity in air, although the actual energy loss is negligible because of the large density difference between the two fluids.

A detailed description of the boundary conditions and the derivation of the characteristic equation can be found in Ref. 1. The surface stiffness is defined as the ratio between the discontinuity in the fluid pressure and the relative fluid displacement at the interface. Table I lists the different bulk and surface wave velocities calculated for dry (air-saturated) and wet (alcohol-saturated) porous glass by neglecting viscosity. Methyl alcohol was used to saturate the porous material since the sintered glass sample happens to be somewhat hydrophobic. Also, the sound velocity in alcohol is 20% lower than in water, therefore the effect to be demonstrated is much stronger in the case of alcohol saturation. The tortuosity was taken to be 1.79, which gives the best agreement between experimental measurements and theoretical predictions for the bulk slow wave velocity in this type of porous glass. On the dry sample, the surface wave velocity is approximately 8% lower than the shear wave velocity, regardless of whether the surface pores are open or closed. On the wet sample, the surface wave velocity is very sensitive to the boundary conditions. For open pores, the surface wave velocity is again approximately 8% lower than the shear velocity, although both velocities are somewhat lower than in the dry sample due to the added inertia of the saturating fluid. On the other hand, for closed pores, the velocity of the true surface wave becomes as much as 40% lower than the shear velocity when the sample is wet.

Feng and Johnson considered completely open \((T=0)\) or closed \((T=\infty)\) surface pores only and assumed viscosity-free flow of the fluid through the pore channels. We extended these calculations to the more general case of arbitrary surface stiffness and, in order to account for viscous losses in the fluid at finite frequencies, we introduced a complex tortuosity \(\alpha(\omega) = \alpha_\omega [1 + (i\omega L)^{1/2}]\), where \(\alpha_\omega\) is the real-valued geometrical tortuosity and \(L\) denotes the viscous loss factor. Figure 1 shows the calculated velocity of the "slow" surface wave propagating on the surface of alcohol-saturated porous glass as a function of the surface stiffness. The velocity drops from 1209 to 745 m/s as the surface stiffness increases. There is a fairly sharp turning point around \(10^7\) N/m², which is in good agreement with previous predictions for the transition range between open- and closed-pore boundary conditions. Figure 1 also shows how the surface wave velocity slightly increases when viscous losses are taken into account. Since the phase velocity of the bulk slow wave decreases with increasing viscous loss, the slow surface wave becomes leaky into the substrate, too.

We are going to show that capillary forces can extend an ideally thin membrane over the surface pores at the boundary with the nonwetting fluid, which is usually so stiff that it assures closed-pore boundary conditions at the surface. For the sake of simplicity, let us assume that the pores are cylindrical holes of radius \(a\). According to the Laplace equation, the radius of the surface membrane is \(R = 2a/(p_0 - dp)\), where \(\sigma\) denotes the surface tension and \(p_0\) and \(dp\) are the hydrostatic and acoustic pressure, respectively. Although there is usually a thin layer of liquid wetting the entire surface of the sample, the thickness of this

<table>
<thead>
<tr>
<th>TABLE I. Calculated sound velocities in dry and wet porous glass.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Fast wave</td>
</tr>
<tr>
<td>Slow wave</td>
</tr>
<tr>
<td>Shear wave</td>
</tr>
<tr>
<td>Surface wave</td>
</tr>
<tr>
<td>open pores</td>
</tr>
<tr>
<td>closed pores</td>
</tr>
</tbody>
</table>

\(\ast\)Rayleigh mode.
\(\ast\)Pseudo-Rayleigh mode.
\(\ast\)Slow surface mode.
layer is so small that viscosity keeps the fluid in it immobile. Assuming that the meniscus is collinear with the surface of the sample, the acoustic pressure changes the fluid volume in the pore by

$$dV = dR \ a^2 \pi / 4R^2 = dP \ a^2 \pi / 8\sigma. \quad (1)$$

By substituting Eq. (1) into the definition\(^1\) of the surface stiffness, we get $T = 8\sigma / \phi a^2$, where $\phi$ denotes the porosity. For a network of cylindrical pores, the combination of the Darcy and Poiseuille laws gives $k_0 = \phi a^2 / 8$ for the static permeability. This well-known formula can be used to approximate the surface stiffness as $T = \sigma / k_0$. For methyl alcohol in contact with air, $\sigma = 2.3 \times 10^{-2} \text{ N/m}$, and even a relatively high static permeability of $\kappa_0 = 10 \text{ Darcy} \approx 10^{-11} \text{ m}^2$ produces a surface stiffness in excess of $10^9 \text{ N/m}^2$. A quick comparison with Fig. 1 verifies that, for all practical purposes, the pores are sealed under these conditions.

Figure 2 shows the schematic diagram of the experimental arrangement used in this study. The surface mode is excited by a vertically polarized shear transducer mounted at the edge of the specimen.\(^7\) The transmitter is driven by a tone-burst of three cycles at 100 kHz. The normal component of the surface vibration is measured by a laser interferometer at two locations separated by 10 mm along the propagation direction. At both axial positions, the laser beam is scanned by $\pm 5 \text{ mm}$ in the lateral direction so that spatial averaging can be used to improve the accuracy of the measurement.

As an example, Fig. 3 shows the time- and spatial-averaged signals for a sintered glass bead sample (Grade 55, Eaton Products) after 5 h of saturation from the bottom of the sample.

FIG. 2. Schematic diagram of the experimental arrangement.

FIG. 3. Detected signals at (a) 10 mm and (b) 20 mm (+10 dB gain) from the transmitter.

FIG. 4. Surface wave velocity (a) and attenuation coefficient (b) vs saturation time for methyl alcohol on a porous glass specimen at 100 kHz.
tom by methyl alcohol. Although the propagation delay is significantly less than the total length of the signal, it can be very accurately determined by calculating the cross-correlation function of the two signals. Figure 4 shows the surface wave velocity and attenuation coefficient as functions of saturation time. Owing to the low viscosity of methyl alcohol, more or less complete saturation is reached within a few seconds after the bottom of the 1 in.-thick sample is soaked. As a result, the velocity quickly drops from 1240 to 1090 m/s and the attenuation increases by almost a factor of two. At this point, the slow wave propagation is still very weak since some of the pores are clogged by trapped air bubbles. At room temperature and atmospheric pressure, it takes approximately 1 h for the alcohol to dissolve the remnant air saturation, thereby opening the blocked pore channels. During this period, the surface wave velocity drops to 840 m/s and the attenuation coefficient increases to 1.1 dB/mm. By adjusting the loss factor in our calculations, we can match the analytical results to the experimental data. Based on the velocity only, the loss factor is approximately 0.03, which produces 1.7 dB/mm attenuation at 100 kHz, i.e., somewhat higher than the measured value. This slight discrepancy might be due to our overestimation of the stiffness of the surface membrane by neglecting the effect of the wetting fluid covering the surface of the sample and the rather crude approximations used in our analytical model for viscous losses.

In conclusion, these experimental results provide clear evidence of the propagation of the new slow surface mode on the free surface of a fluid-saturated porous solid when the pores are closed at the surface by capillary forces. For ordinary solids, the surface wave velocity is always between 86% and 96% of the shear velocity. On the free surface of a fluid-saturated porous solid, the slow surface wave velocity can be as low as 60% of the shear velocity. This phenomenon is a unique feature of permeable solids. Similar measurements conducted on water-saturated natural rocks indicate that the new surface mode can be observed in materials of 200 mD or higher permeability.

This work was sponsored by the U. S. Department of Energy, Basic Energy Sciences Grant No. DE-FG-02-87ER13749.A000. The author wishes to acknowledge the valuable contributions of G. Blaho, R. Ko, and L. Adler.

3The following parameters were used in these calculations (with the notation of Ref. 1): \( \rho_f = 7.9 \times 10^2 \) kg/m³, \( \rho_s = 1.3 \) kg/m³, \( \rho_m = 2.48 \times 10^3 \) kg/m³, \( K_f = 1.03 \times 10^8 \) N/m², \( K_s = 1.5 \times 10^5 \) N/m², \( K_m = 4.99 \times 10^{10} \) N/m², \( K_b = 5.66 \times 10^3 \), \( N_s = 3.15 \times 10^8 \) N/m², \( \phi = 0.3 \), \( \alpha = 1.79 \).