Morphology versus acoustic features of permeo-elastic materials

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1 Introduction

This article focuses on the acoustic properties of porous media featuring a rigid solid skeleton with attached highly-flexible elastic films.This type of media can correspond, for example, to foams, with the thin membranes playing the role of films and the rigid structure being formed by their thicker struts. Such permeo-elastic media are characterized by the pore-scale fluid/film interaction effect which, compared to conventional porous media, enriches the flow physics with an elastic component. For this reason, the acoustic characteristics of permeo-elastic media can differ considerably from those of conventional porous media, see e.g. [1], [2].
However, such materials may have different morphologies depending on whether the pores or membranes are partially or fully connected. In this article it is shown that these morphological aspects play an essential role on the acoustic properties of these materials. We will successively examine the cases of permeo-elastic materials with pores that are: :
- Fully connected, i.e. no pores are closed by the films,
- Unconnected, i.e. all pores are closed by films,
- Partially connected, i.e. some pores are closed by the films.

To this end, by assuming acoustics wavelenghts much larger than the characteristic pore size, the two-scale asymptotic homogenization method have been used. The derived upscaled models enables to identify the different wave propagation regimes. In the following we will mainly present the assumptions and the results to which they lead. The theoretical developments will be reported in a forthcoming publication.

2 Fully connected pores

This case was investigated in [1], [2]. The main aspects are now recalled. Due to the separation of the scales and the fact that the pores are fully connected, the pressure at the dominant order is uniform in the pores, i.e. $P = P^0(x)$. The gas flow as well as the film movements are forced by the macroscopic pressure gradient. The local velocity field (of the gas and the films) results from the effects of the gas viscosity, the elasticity of the films (treated as bending plates and/or as tensioned membranes) and the inertia of the gas and the films. Thus, in a permeo-elastic medium, the constitutive law of flow which replaces the dynamic Darcy's law is of an elasto-visco-inertial nature. Moreover, the macroscopic mass balance is not altered by the thin films and is formally the same as in classical porous media (including thermal effects). For these materials three different flow regimes can be distinguished:

- At low frequencies, the films tend to behave in a quasi-rigid way and the flow is close to that of the porous medium (MP_0) for which the films would form part of the rigid skeleton. Nevertheless, the correction due to the films results in an elastic component which is added *in series* to the dynamic permeability of (MP_0),

- At high frequencies, the films tend to behave as if they were infinitely flexible and the flow is close to that of the porous medium (MP_∞) in the absence of films, but with an effective fluid/film mass. The correction provided by the films results in an elastic component which is added *in parallel* to the dynamic permeability of (MP_∞),

- At intermediate frequencies, the elastic effects become significant and combine with viscous and inertial effects. In particular, weakly damped internal resonance and anti-resonance regimes may develop. This situation is of interest for acoustics because in this frequency range the medium is quasi-lossless with a negative effective density that results in non-propagative waves.

3 Unconnected pores

In this case, although all pores are closed, *in accordance with the long wavelength hypothesis*, the pressure at the dominant order fluctuates on a macroscopic scale, i.e. $P = P^0(x)$. Thus, the developments are formally the same as in the previous case and the law of flow is also of an elasto-visco-inertial nature. Furthermore, the mass balance takes the same form as in classical porous media. However, as a consequence of the fact that the pores are closed, the average flow in the pores is entirely determined by the movement of the films. Consequently, the different flow regimes are as follows :

- At low frequencies, since films tend to behave in a rigid manner, the flow tends to fade and the medium to be impermeable. However, the macroscopic pressure gradient sets the films in motion and therefore the constitutive law of flow is dominated by the elasticity (and inertia) of the film. This *"elastic permeability"* is corrected by the visco (inertial) effect in the gas. The acoustic characteristics of the waves are therefore similar to those of weakly damped and weakly dispersive viscoelastic waves, and differ significantly, qualitatively and quantitatively, from those of low-frequency acoustic waves in conventional porous media.
- At intermediate frequencies, the elastic effects become strong and weakly damped; the internal resonance and anti-resonance of the gas cells coupled to the films appear, resulting in negative density and non-propagative waves.
- At high frequencies, since the films appear to be infinitely flexible, the flux is close to that of the porous medium (MP_∞) in the absence of films (again with a fluid/film effective mass). As in the case of connected pores, the presence of films introduces an elastic component which is added in parallel to the dynamic permeability of (MP_∞). This high frequency description applies only in the frequency range of scale separation. Above this range, internal dynamic phenomena (as local "breathing" modes) involving two or more cells may appear and leads to a more complex physics of acoustic waves.

4 Partially connected pores

In this morphology the pressure at the dominant order in the connected pores fluctuates at the macroscopic scale i.e. $P = P^0(x)$. In pores closed by films another pressure field P' can prevail, and the difference between the two pressures is balanced by the elasticity of the films. However, at the leading order, to respect the scale separation and the condition of local incompressibility the motion of the film must necessarily be of a lower order than that of the gas. Hence, at the dominant order the films are immobile. Thus, the gaz flow is identical to that which would develop in a rigid porous medium with the connected pores only. In this case we find the Darcy's classical visco-inertial law.
On the other hand, the contribution of the closed pores intervenes in the mass balance, and brings a correcting term to the effective compressibility. The said correction results from the elasto-inertial (and weakly dissipative by viscosity) behavior of the resonator constituted by the film and volume of the trapped gas.
Thus at low and high frequencies we find an usual behavior. Conversely in the local resonance frequency range an unconventional dispersion of acoustic wave can be observed as the effective compressibility is significantly modified and may even become negative.

5 Conclusion

In conclusion, while it is well known that the morphology plays a determining role in porous media, it seems its influence is even more important for permeo elastic media, for which they can lead to a drastic qualitative and quantitative change of acoustic behavior.

References

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