Porous Foams with Active Implants Improving Acoustic Absorption

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1 Introduction

There are apparent reasons for an advanced modeling of porous media with distributed masses and solid implants which should be at the same time sufficiently accurate and efficient to allow a reliable optimization of such poroelastic composites. Recent experimental investigations report a significant improvement of the insertion loss of standard acoustic blankets at lower frequencies by the addition of randomly placed masses to the poroelastic layers [1]. They show that the improvement by distributed masses (implants) tend to be greater than the one due to the mass effect alone. The acoustic absorption of multi-layer absorbers with different inner structures has also become a subject of research [2]. The proposed modeling was accurate with respect to the geometry (thanks to the finite element approach), however, the porous medium was modeled by using the so-called fluid-equivalent approach which generally assumes that the frame (solid skeleton) of a porous medium is rigid. For many porous materials such approach gives good predictions in higher frequencies and for certain configurations.

The present work presents an accurate multiphysics modeling and analysis of active porous-composite sound absorbers composed of a layer of poroelastic material (a porous foam) with embedded elastic implants having active (piezoelectric) elements. The purpose of such active composite material is to significantly absorb the energy of acoustic waves in a wide frequency range. At the same time the total thickness of composites should be very small. The active parts of composites are used to adapt the absorbing properties of porous layers to different noise conditions by affecting the so-called solid-borne wave (originating mainly from the vibrations of elastic skeleton of porous medium) to counteract the fluid-borne wave (resulting mainly from the vibrations of air in the pores); the both waves are strongly coupled, especially, in lower frequencies. Passive and active performance of the absorbers is analysed to test the feasibility of this approach. Since the absorption should be actively improved by affecting the vibrations of the elastic skeleton of porous layers, it is apparent that the rigid-frame modelling cannot be used here. Instead, the advanced biphasic theory of poroelasticity (ref. [3, 4]) must be used to model porous material of the active absorbers. For time-harmonic analysis it is efficient to use the so-called mixed displacement–pressure formulation of the Biot's poroelasticity (ref. [5, 6]).

The examined application of active porous composites links several mathematical models of single- and multiphysics, namely:

- the Biot's theory poroelasticity – to model the material of porous layer (with the air-filled pores),
- the linear elasticity – to model elastic implants,
- the piezoelectricity – to model the active parts (piezo-actuators) of implants which affect the lower frequency vibrations of the elastic skeleton of a porous medium.

All these problems are strongly coupled and the consideration of this mutual interaction of different media is very important. Thus, a coupled multiphysics model of a system made up of poroelastic, elastic, and piezoelectric media was constructed using the Galerkin finite element method.

2 Acoustic absorption of poroelastic layers

The main purpose of the present analysis of poroelastic layers with solid implants is to asses how passive and active implants can influence the acoustic absorption of layers. The acoustic absorption of a poroelastic layer fixed to a rigid wall and subject to a plane acoustic wave propagating in the air onto the layer surface at normal incidence will be computed as follows [4]. First, the acoustic impedance at normal incidence is determined at the interface between the poroelastic layer and the air:

$$Z = \frac{p_0}{v}\,, \quad \text{where} \quad v = \mathrm{j}\,\omega\, u_1^{\mathrm{t}} = \mathrm{j}\,\omega\left[(1-\phi)\,u_1 + \phi\,U_1\right]. \tag{1}$$

Here, v is the velocity of the propagating wave at the layer–air interface (continuous across this boundary) whereas p_0 is the wave pressure. As a matter of fact the (complex) amplitudes are used here, (nb. $\mathrm{j} = \sqrt{-1}$). For time-harmonic vibrations the velocity v at the interface of a poroelastic material depends on the angular frequency $\omega = 2\pi f$ (f is the frequency), and on the total (normal) displacements of the poroelastic layer u_1^{t}, which by itself is composed of the porosity-dependent contributions of the displacements of solid phase u_1 and fluid phase U_1 (ϕ is the porosity).

Now, the reflection coefficient in is computed:

$$R = \frac{Z - Z_0}{Z + Z_0}\,, \tag{2}$$

where $Z_0 = \varrho_0\, c_0$ is the characteristic impedance of the air (ϱ_0 is the air density and c_0 the speed of sound). Finally, knowing the reflection coefficient, the acoustic absorption coefficient can be determined:

$$A = 1 - |R|^2\,. \tag{3}$$

This final property is real-valued (unlike the reflection coefficient R, and the impedance Z, which are complex).

Figure 1 presents a layer of porous foam with *T-shaped* implants made up of stripes of 0.3 mm-thick aluminium foil fixed to the the active PZT-elements. The analysis consisted in determining the acoustic absorption of such active/passive poroelastic composites. To this end, the results of finite-element analysis (especially, u_1^{t} at the layer's surface) were used by the analytical formulas for the impedance, the reflection and absorption coefficients. These formulas result from a one-dimensional analysis of the plane wave propagation which is slightly violated if the solid implants are present (notice, however, that the implants are set approximately 7 mm form the surface of the free-interface). Therefore, the absorption coefficient was computed in two points of the layer surface: at $x_2 = 0$ mm and $x_2 = 5$ mm (see Figure 1), providing two limit-values. It was checked that in the considered frequency range the two values are almost always very similar and thus, for the sake of clearness, only the average curve is plotted in the graph presented below.

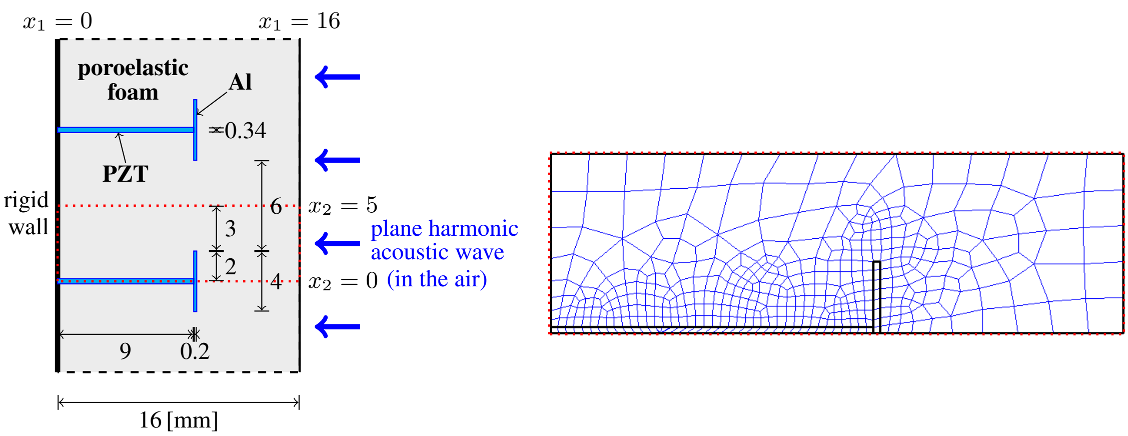

Figure 1: *Active composite configuration and the finite-element mesh of the modeled representative subdomain*

3 Active improvement of the acoustic absorption of poroelastic composites

The general idea of active improvement of the acoustic absorption of poroelastic composites can be explained as follows:

- A harmonic acoustic wave propagates in the air onto the interface between the air and a poroelastic layer (or composite). Higher frequency waves can be well absorbed by the layer but at lower frequencies the acoustic absorption of thin layers is very poor.
- Now, the acoustic wave continues to propagate in the porous medium and is reflected by the rigid wall. In fact, there are three waves: a slow longitudinal wave in the fluid phase (the so-called fluid-borne wave in the 'smeared' air of the pores), a fast longitudinal wave in the solid phase (the so-called solid-borne wave in the 'smeared' elastic skeleton) and a shear wave in the solid phase. At lower frequencies all these waves are strongly coupled so that the vibrations of elastic skeleton are coupled with the vibrations of the air in the pores.
- Because of this coupling the acoustic absorption may be actively modified by affecting the vibrations of the elastic skeleton. To this end, active implants are embedded into the porous layer and an appropriate harmonic excitation signal is applied onto the electrodes of the piezoelectric parts of the implants.

The results presented in this section show the feasibility of this approach.

The fixed parts of he T-shaped implants can be active – they are thin patches of piezoelectric ceramic PZT4, through-thickness polarized, 9 mm long and 0.34 mm thick (see Figure 1). It was checked that by applying a voltage onto their electrodes these piezo-patches would stretch almost 10^{-8} m/V, which means that, for example, a signal with the amplitude of 20 V would extend the active implant for nearly 2×10^{-7} m. Notice that this amplitude is of the same order of magnitude as the maximal amplitude of vibrations of the elastic skeleton of the considered porous layer subject to a harmonic noise of 100 dB. Thus, the active implants may affect the vibrations of elastic skeleton in order to improve the acoustic absorption of the active poroelastic composite. The results presented below prove the feasibility of this assumption.

Figure 2 shows passive and active absorption curves of the porous layer with active and passive implants, or without implants. The frequency range reaches 2600 Hz – above this frequency the passive absorption of the layer with implants was very good (from 0.8 to 1.0) and almost identical with the

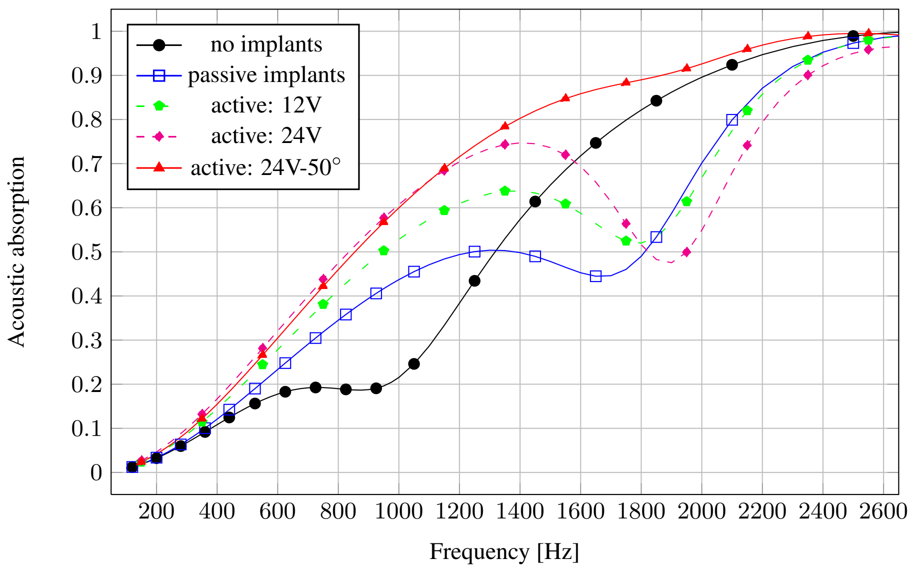

Figure 2: *Active and passive absorption curves for the porous composite/layer*

absorption of the layer with no implants. As mentioned above, to actively improve the absorption a harmonic excitation signal is applied onto the electrodes of the piezoelectric parts of the T-shaped implants. The frequency of the signal equals to the frequency of the acoustic wave, and for the considered range the same constant voltage amplitude is assumed. Three cases are presented which differ by the value of the amplitude and phase of voltage signals (the phase angle of $0°$ means the maximal extension of the implant): (1) 12 V (no phase shift), (2) 24 V (no phase shift), (3) 24 V with the phase of $50°$. In general, all signals improve the acoustic absorption of the composite, however, only the one with the phase shift gives always better absorption than the layer without implants. For lower frequencies the improvement is very weak, and for very low frequencies the absorption is very poor which is obvious when one remembers that the porous layer has only 16 mm. Another interesting observation is that the phase shift effect tends to be visible only when the frequency increases.

4 Conclusions

The obtained results allow to draw the following general conclusions:

- The proposed T-shaped implants (in the passive state) improve the acoustic absorption of a thin porous layer in some range of lower frequencies (where the absorption is poor), but can decrease it in another range of higher frequencies (where altogether, the absorption is better). Similar statement is also valid for stripes of aluminium foil embedded inside the porous layer. For the lowest frequencies and above some high frequency there is no difference in the absorption curves of the porous layer with or without implants.

- The actuators in the form of thin patches of PZT ceramic are able to extend enough to affect the vibrations of the elastic skeleton of polyurethane foams induced by acoustic waves. This influence is better for the proposed T-shaped implants.

- At lower frequencies the coupling between the solid-borne waves (of the elastic skeleton) and the fluid-borne wave (of the air in the pores) is strong enough to allow the exploitation for the improvement of acoustic absorption by the proposed active approach.

- Electric signals with the amplitudes of the order of magnitude of 10 or 20 V, applied to the active piezoelectric parts of the implants, give significant improvement of the acoustic absorption of porus composites subject to the acoustic pressure excitation of 100 dB. A phase shift in the signal is necessary to achieve this improvement in the whole frequency range of interest, although it is important only above some frequency (below its effect is insignificant).

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