ANALYSIS OF WAVE PROPAGATION AND ABSORPTION AT NORMAL AND OBLIQUE INCIDENCE IN POROELASTIC LAYERS WITH ACTIVE PERIODIC INCLUSIONS

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ABSTRACT

The paper presents numerical studies of wave propagation under normal and oblique incidence in sound-absorbing layers of poroelastic composites with active and passive inclusions embedded periodically along the composite layer surface. The purpose of active inclusions is to increase the mass-spring effect of passive inclusions attached to the viscoelastic skeleton of the poroelastic matrix of the composite in order to increase the dissipation of the energy of acoustic waves penetrating into such a layer of poroelastic composite. Finite element modelling is applied which includes the coupled models of Biot-Allard poroelasticity (for the poroelastic matrix), piezoelectricity and elastodynamics (for the active and passive inclusions, respectively), as well as the Helmholtz equation for the adjacent layer of air. The formulation based on the Floquet-Bloch theory is applied to allow for modelling of wave propagation at oblique incidence to the surface of the periodic composite layer. The actively exited piezoelectric inclusions may become additional (though secondary) sources for wave propagation. Therefore, a background pressure field in a wide adjacent air layer is used to simulate plane waves propagating from the specified direction, oblique or normal, onto the poroelastic layer surface, and a non-reflecting condition is applied on the external boundary of the air layer.

1. INTRODUCTION

Enhancement in acoustic performance of porous treatments due to various inclusions was reported in many works, e.g. experimentally in [1], numerically in [2–7] using equivalent-fluid models for porous materials, and in [8–10] using poroelastic modelling. These and many other works focus on passive inclusions.

The concept of active acoustic foams was proposed and studied in experimental works [11–13] on the application of control algorithms to polyurethane foams with pieces of piezoelectric PVDF film embedded inside. Smart foams with a PVDF film as an active inclusion were also investigated in [14, 15] performing finite element analyses involving poroelastic finite elements, as well as experimental validations of their performance in the passive state.

Hybrid active-passive acoustic panels with poroelastic core and aluminium faceplates with actuators in the form of piezoelectric patches were studied in [16–18]. An experimental research on similar panels was also conducted in [19]. Active absorbers proposed in [20–22] used a control system to cancel the acoustic pressure at the rear face of a porous layer. In that way, a purely real impedance at the front face was obtained; it was demonstrated that its value depended only on the resistivity and thickness of the porous material.

The sound absorption of poroelastic composites with active piezoelectric inclusions was examined in [23, 24] using fully-coupled models. The present work effectively combines the approaches proposed in [8, 23–25] and also investigates the influence of the active approach on the partial absorption coefficients related to various dissipation mechanisms, i.e. due to viscous and thermal losses in the pore-fluid, and structural losses in the viscoelastic skeleton, in a way similar to the one applied for passive inclusions in [10].

2. PROBLEM DESCRIPTION: CONFIGURATIONS AND MODELLING APPROACHES

Figure 1 shows the problem configuration as well as finite-element meshes and boundary conditions used in numerical analyses. The configuration consists of two layers:

- a poroelastic composite layer backed by a rigid wall,
- an adjacent layer of air in front of the composite layer.

The thickness of the poroelastic composite is 30 mm and the assumed air layer thickness is three times that value. The composite is made of poroelastic foam and contains two inclusions of different types in a periodic cell 20 mm wide. In other words, both types of inclusions are periodically embedded every 20 mm along the surface of the composite layer. The detail in Figure 1 shows the size, shape, and arrangement of both inclusions in the periodic cell: one is a thin plate of PZT material (0.25 mm wide by 10 mm long) and the other is a round steel bar (1 mm in diameter). The steel inclusion is located 10 mm from the free surface of the composite (or in fact, from the interface

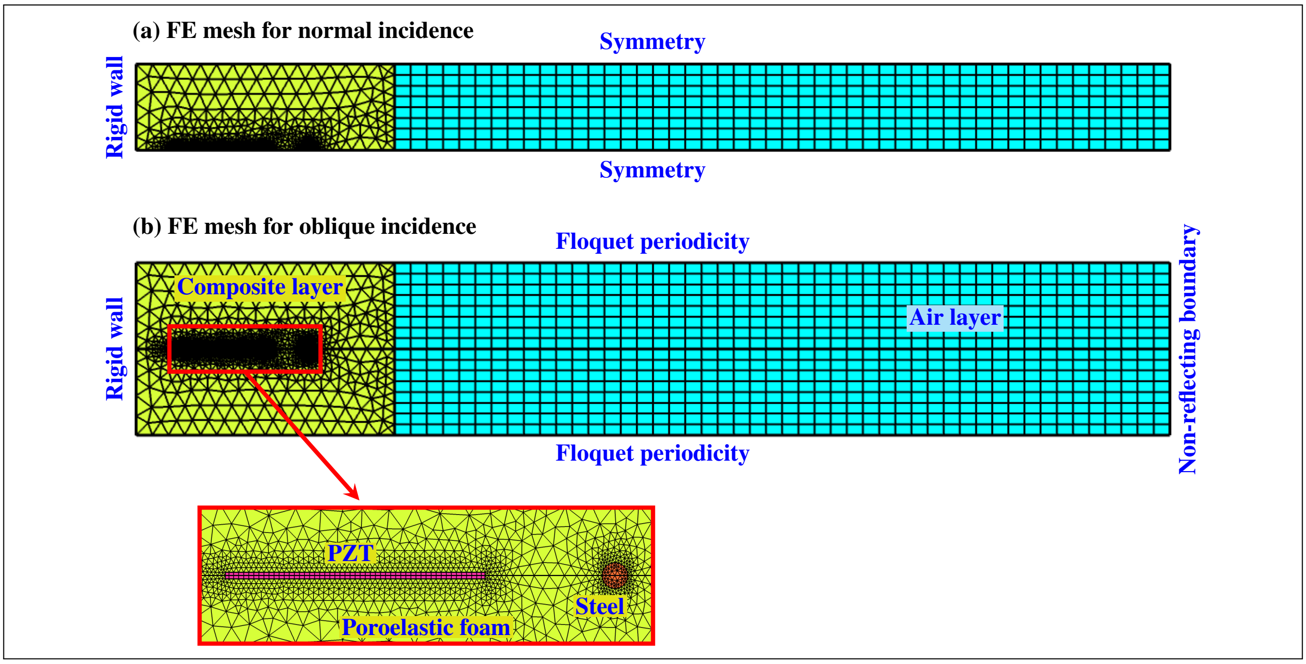

Figure 1. Problem configuration, boundary conditions, and finite-element meshes used for: (a) normal incidence, and (b) oblique incidence of plane harmonic waves.

between the porous and air layers), which means 20 mm from the rigid wall. The PZT inclusion is located between the rigid wall (5 mm from it) and the steel inclusion (the distance between the inclusions is 5 mm).

The problem is modelled as two-dimensional assuming plane strains (the configuration remains unchanged in the direction perpendicular to the problem plane depicted in Figure 1) and a coupled system [26, 27] including:

- the Biot-Allard model [28–35] for the poroelastic foam of the composite layer;
- the Helmholtz equation for the air layer;
- equations of linear isotropic elasticity (elastodynamics) for the steel inclusion;
- a fully-coupled piezoelectric model [36] (i.e. anisotropic elastodynamics coupled with electrostatics) for the PZT inclusion.

The piezoelectric inclusion can also be modelled in a simpler way [24, 25] by using the thermoelastic analogy or (equivalently) by means of initial strains applied to the anisotropic elastic material, because the electric field due to the acoustically induced vibrations can be neglected and only the inverse piezoelectric effect (induced by the electric control signal) need to be considered.

Finite-element calculations are carried out to analyse the time-harmonic problem in the frequency range from 100 Hz to 1.5 kHz using two computational domain cases with dedicated FE meshes depicted in Figure 1. The one shown in Figure 1(a) contains only half of the periodic composite cell by taking advantage of the configuration symmetry and can only be used for numerical analyses of wave propagation with normal incidence on the surface of the composite layer. As a consequence, in this case, symmetric mechanical boundary conditions are applied on upper and lower edges of such 'half-cell' computational domain, see Figure 1(a). The reflection coefficient, which is used to determine the acoustic absorption of the poroelastic composite layer, can be calculated from the surface acoustic impedance averaged on the interface between the poroelastic domain and the adjacent air layer, or on any other surface in the air layer, because the propagation of acoustic waves in this layer is lossless.

The computational domain shown in Figure 1(b) is twice as large as the 'half-cell' domain and combines the FE mesh generated for the smaller domain as well as its mirrored copy about the symmetry surface, i.e. the lower edge of symmetry of the 'half-cell' domain. The 'full-cell' computational domain has to be used for analyses of the propagation of acoustic waves with oblique incidence. In such analyses, a background sound pressure field is applied in the air layer simulating an ingoing plane wave (with an amplitude of 1 Pa) propagating onto the composite layer – from a certain oblique direction (e.g. at an angle of 30° to the normal direction). Consequently, formulations based on the Floquet-Bloch theory [6, 37] are used for all models (i.e. Helmholtz, Biot, and elastodynamic equations) and Floquet periodicity is applied along the periodicity edges, while a non-reflecting boundary condition [6] at the "external" boundary of the air layer, see Figure 1(b). The reflection coefficient, necessary to determine the acoustic absorption of the poroelastic composite layer, can be calculated at any point in the air layer (because the wave propagation in this layer is lossless) as the ratio of the scattered pressure field to the background pressure.

The porolelastic composite is analysed in its passive and active state. In the passive state, no signal is sent to the electrodes on the side surfaces of the PZT inclusion and the piezoelectric inclusion is shunted, i.e. both electrodes are grounded. In the case of the active state, a control signal is applied with a constant amplitude U_{amp} and a frequency-dependent optimised phase (relative to the phase of the signal measured for the incident pressure wave). The control signal effect is modelled using electrical boundary conditions, i.e. voltage (electric potential) $+\frac{1}{2}U_{\mathrm{amp}}$ applied on the upper side surface of the PZT inclusion and $-\frac{1}{2}U_{\mathrm{amp}}$ applied on the lower side surface. This is in the case of the 'full-cell' configuration. In the case of the 'half-cell' configuration, only the upper half of the PZT inclusion is present in the computational domain and its lower side (i.e. the mid-surface of the PZT inclusion) is grounded, which is due to the anti-symmetry of the electrostatic problem.

3. RESULTS OF NUMERICAL ANALYSES: OBSERVATIONS AND DISCUSSION

Figure 2 compares the distribution of acoustic pressure in the air layer for plane harmonic waves propagating into the composite layer at normal incidence, see Figure 2(a), and at oblique incidence, see Figure 2(b). For the sake of this comparison, a relatively high frequency of 6 kHz was chosen to better demonstrate the wave interference pattern near the surface of the composite layer. In the case of normal incidence, the interference from incident and reflected waves produces a wave pattern that is still plane even very close to the surface of the composite layer, while in the case of oblique incidence, the pattern is more complex due to the interference of waves reflected from the surface of the poroelastic composite as well as from the inclusions inside the composite and the rigid wall.

The results of sound absorption are calculated for the poroelastic layer subject to the acoustic pressure wave at normal incidence and compared in Figure 3 for three cases:

(a) the 30 mm-thick reference layer of homogenoeus poroelastic foam (for comparison purposes),

(b) the 30 mm-thick composite layer of the poroelastic foam with passive inclusions (i.e. in passive state),

(c) the active composite layer.

In each case the acoustic absorption is presented along with the partial absorptions related to: viscous, thermal, and structural dissipation effects due to the fact that at each frequency f, the (total) acoustic absorption coefficient $A_{\mathrm{tot}}(f)$ can be decomposed as follows [38, 39]

$$A_{\mathrm{tot}}(f) = A_{\mathrm{vis}}(f) + A_{\mathrm{thm}}(f) + A_{\mathrm{str}}(f), \quad (1)$$

where the viscous $A_{\mathrm{vis}}(f)$, thermal $A_{\mathrm{thm}}(f)$, and structural $A_{\mathrm{str}}(f)$ partial absorption coefficients are complementary fractions of the total absorption, related to the corresponding time-averaged powers $P_{\mathrm{vis}}(f)$, $P_{\mathrm{thm}}(f)$, $P_{\mathrm{str}}(f)$ dissipated due to viscous, thermal, and structural effects,

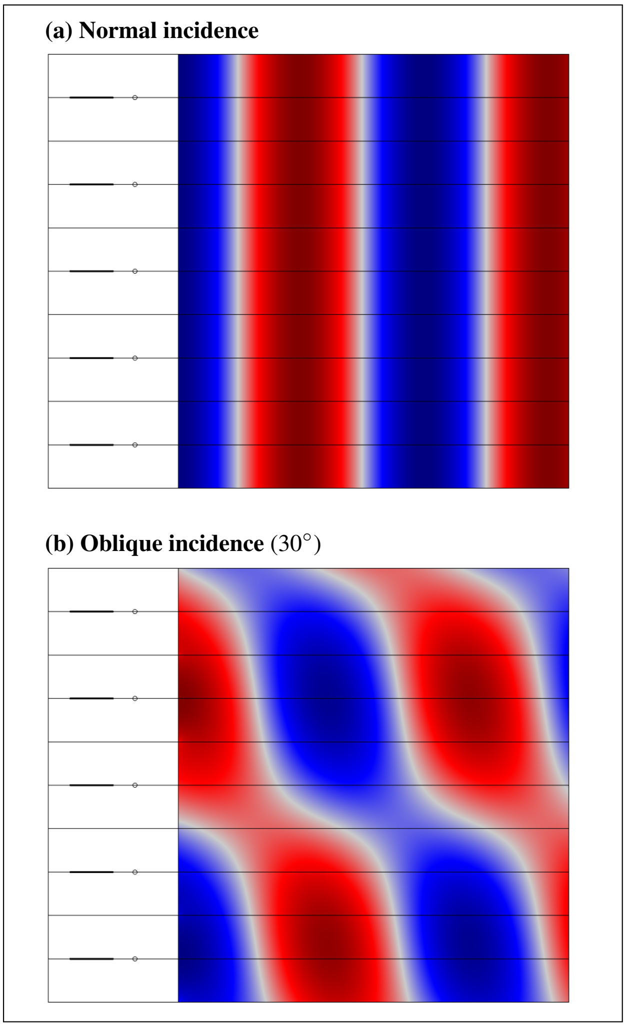

Figure 2. Acoustic pressure field (real part) in the adjacent air layer at 6 kHz for: (a) normal incidence and (b) oblique incidence (30° from the normal direction) of plane waves.

respectively, i.e.

$$A_{\mathrm{vis}}(f) = \frac{P_{\mathrm{vis}}(f)}{P_{\mathrm{tot}}(f)} A_{\mathrm{tot}}(f), \quad (2)$$

$$A_{\mathrm{thm}}(f) = \frac{P_{\mathrm{thm}}(f)}{P_{\mathrm{tot}}(f)} A_{\mathrm{tot}}(f), \quad (3)$$

$$A_{\mathrm{str}}(f) = \frac{P_{\mathrm{str}}(f)}{P_{\mathrm{tot}}(f)} A_{\mathrm{tot}}(f). \quad (4)$$

Here, the total power dissipated in the poroelastic medium is the sum of all contributing powers, viz.

$$P_{\mathrm{tot}}(f) = P_{\mathrm{vis}}(f) + P_{\mathrm{thm}}(f) + P_{\mathrm{str}}(f). \quad (5)$$

The partial powers $P_{\mathrm{vis}}(f)$, $P_{\mathrm{thm}}(f)$, $P_{\mathrm{str}}(f)$ are calculated by integration of relevant dissipation effects in the poroelastic domain only, because wave propagation in solid inclusions and air layer is lossless. It should be noted that the 'viscous' and 'thermal' effects mean the relevant losses in the fluid saturating the pores, while the 'structural' effects mean the losses due to the deformation of the viscoelastic skeleton of the poroelastic foam. This deformation may

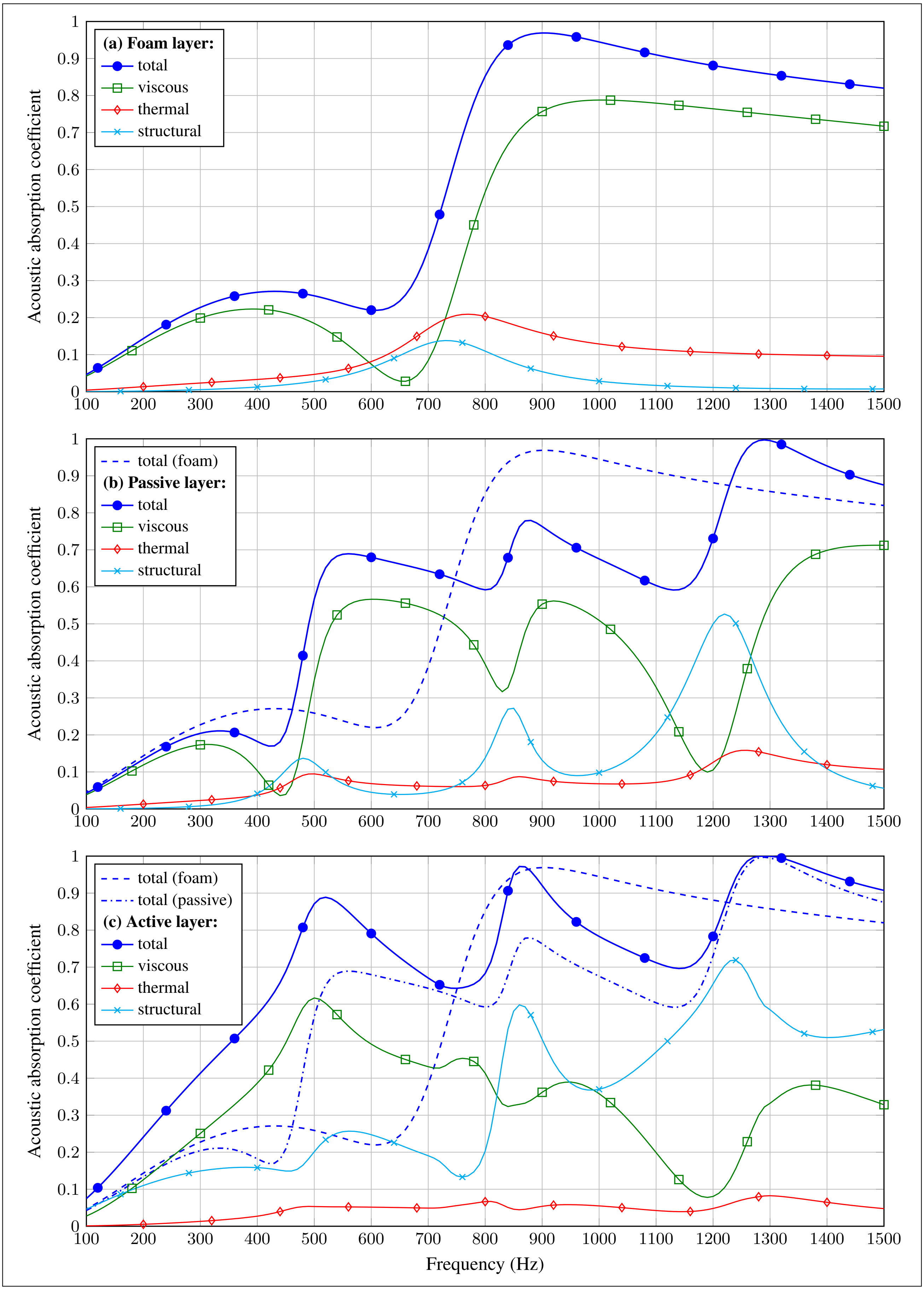

Figure 3. Total and partial acoustic absorptions at normal incidence for: (a) homogeneous poroelastic foam layer, (b) passive layer of poroelastic composite, (c) active layer of poroelastic composite.

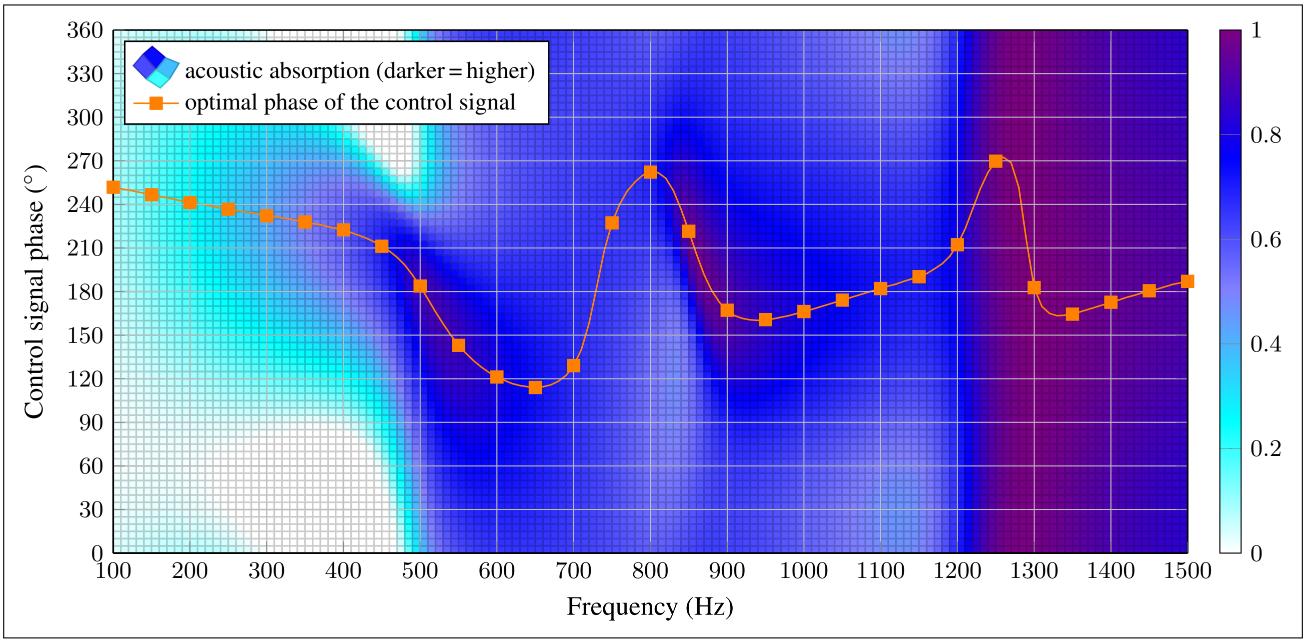

Figure 4. Optimised phase of the most effective control signal (with voltage amplitude of 60 V) acting on the PZT inclusion.

be strongly influenced by the presence and motion of solid inclusions attached to the skeleton of the poroelastic foam, and in the case of the active approach, also by the motion induced by the control signal applied to the electrodes of the PZT inclusion.

Based on the results presented in Figure 3(a), the following observations can be made regarding the sound absorption of the homogeneous poroelastic foam:

- the acoustic absorption of the homogeneous layer of the poroelastic foam is mainly due to viscous losses;
- the only exception is the low absorption around the resonant frequency of the elastic skeleton, where the viscous effects are weak, because the solid phase (i.e. skeleton) of the poroelastic foam follows the fluid phase;
- structural losses due to the deformation of the viscoelastic skeleton are even smaller (in the whole frequency range) than the thermal losses due to the compression and decompression of the air in the pores.

When considering the results of the numerical analysis performed for the poroelastic composite in the passive state, see Figure 3(b), and comparing them with the results for the homogeneous layer, the observations are more varied, viz.:

- in the target frequency range below 700 Hz, the viscous dissipation effects and overall acoustic absorption are enhanced;
- the skeleton resonance is shifted to a lower frequency as the inclusion mass is added to the poroelastic layer of the composite;
- the absorption peak associated with the so-called quarter-wavelength resonance is shifted from 900 Hz to 550 Hz; this peak absorption is now around 0.7 (i.e. not nearly perfect as before);
- at higher frequencies (from 740 Hz to 1230 Hz) the total absorption is slightly reduced by the presence of solid inclusions;
- two absorption peaks appear at higher frequencies due to the mass-spring effect of the inclusions attached to the skeleton of the poroelastic foam; they are mainly due to structural losses in the viscoelastic frame of the foam.

For the poroelastic composite in the active state, the optimal phase is first found for the control signal applied to the electrodes on the PZT inclusion, see Figure 4. Then, the total and partial absorption coefficients are determined as shown in Figure 3(c), finally allowing the following observations based on a comparison with the previous results:

- even more significant absorption enhancement is gained in the target frequency range (i.e. below 700 Hz) thanks to the active approach using a control signal with an amplitude of 60 V and well-chosen phase;
- this improvement is mainly due to viscous losses, but also due to structural losses in the viscoelastic skeleton;
- the phase of the effective control signal does not have to be very precisely selected, especially at higher frequencies, see Figure 4;
- higher-frequency absorption peaks are mainly due to increased structural losses in the viscoelastic skeleton.

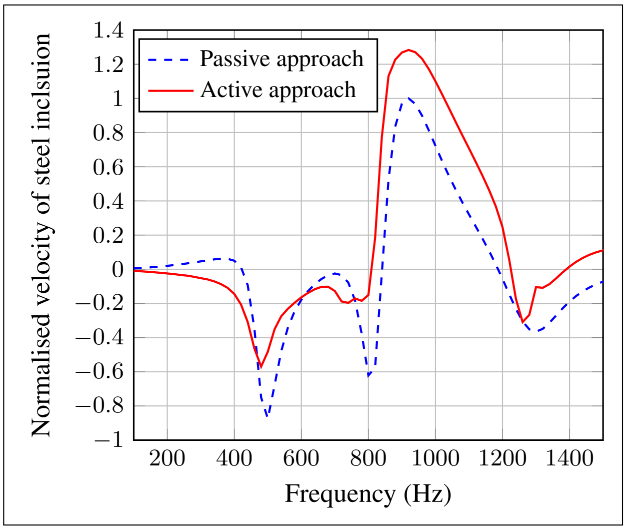

Figure 5. Normalized (dimensionless) velocity of the steel inclusion in the case of the passive and active approach.

4. CONCLUSIONS

Small passive inclusions periodically embedded in a poroelastic layer can significantly change its sound absorption performance at lower frequencies. The mass-spring effect of an inclusion attached to the viscoelastic skeleton affects the movement of the solid phase, typically increasing absorption in the lower frequency range, due to greater viscous losses in the fluid interacting with the skeleton, but also due to losses in the viscoelastic skeleton. The active approach allows to control and increase this effect by influencing the movement and velocity of passive inclusion with the active one (see Figure 5).

5. ACKNOWLEDGEMENTS

The financial support from project "Relations between the micro-geometry and sound propagation and absorption in porous and poroelastic media" financed by the National Science Centre (NCN), Poland, under Grant Agreement No. 2015/19/B/ST8/03979, is gratefully acknowledged.

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