Vibro-acoustic energy propagation in anisotropic, anelastic porous materials

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ABSTRACT: Historically, the modelling of the acoustics of poro-elastic materials (APEMs) has assumed the materials to be isotropic in both their elastic as well as their acoustic properties including the dissipative mechanisms related to viscous, inertial and thermal interactions. While this is a reasonable approximation when the absorption of sound is of interest, it fails to provide meaningful results for most foamed materials in general and for certain sets of boundary conditions involving elastic contact with solids or other APEMs in particular. A general modelling of fully anisotropic APEMs will be reviewed and taken as a starting point for a series of numerical experiments focussing on aspects of propagation of vibro-acoustic energy, in a homogeneous layer as well as in multiple layer arrangements. From previous works it is known that the influence of anisotropy may be quite significant, in particular for structure-borne vibro-acoustic energy. In addition, it is known that the alignment of principal directions may have substantial influence on the transmission of vibro-acoustic energy. These findings will be recalled in order to prepare for a discussion on the aspects of the directional dependence of the anelastic moduli which will be the core of the presentation at the conference. Real material tensors may be constructed from a superposition of these anisotropic contributions, in the most general case, not necessarily sharing the same principal directions. Starting from these fully anisotropic constitutive tensors with general symmetry properties, studies of optimal alignment between conservative and dissipative tensors, as well as between different materials in various configurations of interest, will be illustrated in the lecture.

KEY WORDS: Anisotropic; Anelastic; Poro-elastic materials; Acoustics; Vibrations.

1 INTRODUCTION

Introducing porous materials as elasto-acoustic dissipative components in multilayered structures is a well established way of handling noise and vibration problems. Their low weight combined with their multi-functional character make them quite attractive in a wide range of demanding applications, such as automotive, aerospace, railway, etc. With the increasing interest in reducing the vehicle body weight in order to lower the environmental impact of transportation there is a growing need to model such materials with a high degree of fidelity. In many applications of porous materials, the assumption of isotropic properties yields satisfactory correlations between experimental and computed results. This is particularly true in cases where airborne sound absorption is of interest. However, in situations where the structure-borne properties are important, the sources of differences between predicted and measured results are not fully understood. Biot generalized the theory of porous material to anisotropic modeling [8], opening up for a new research front in the acoustics of poro-elastic materials. Apart from being an interesting subject in itself, this has recently raised questions related to the possible influence of the potentially anisotropic character of poro-elastic materials, including the potential for tailoring of such properties, should they be known in sufficient detail. Both these are within the scope of the present work, aiming at exploring whether the possible anisotropy of the constitutive properties may be important enough to influence the performance, thus possibly explaining the above mentioned discrepancies, to a significant extent. To provide necessary and meaningful data, as well as application cases appropriate for simulations, for such an investigation, material models of anisotropic poro-elastic materials together with proper simulation tools are required. Both these topics are at the front of the research for the acoustics of poro-elastic materials, as an example is the characterization of the acoustic parameters still an issue where more research is needed [16] as complete determination of the acoustic parameters of anisotropic foam requires both time, experience and development of new advanced measurement and estimation techniques [10, 11, 14, 26]. In addition, simulation models allowing for parametric studies are necessary in order to assess the influence of anisotropy on the vibro-acoustic behavior of structures comprising porous materials [13, 18, 19].

The objective of the present work is to study the performance sensitivity of orthotropic materials, in a numerical experiment. It is an extension of previously published work, focussing on some of the results of the numerical experiment, [21]. The focus is on the influence of anisotropy in general, and on the effects of aligning two layers of the same material relative to each other in particular. The simulation set up is composed of two layers of porous material in contact with an aluminum plate along one surface and separated from an identical plate through an air gap along the opposite. This particular set up has been chosen in order to stress the influence of both elastic and acoustic properties on the response behavior [11, 13]. The sensitivity is analyzed through the solution of an optimization problem using previously published techniques [22]. Clearly there is a need to set an appropriate level of complexity of the anisotropic
material models used in this preliminary investigation. While a completely general material model would imply that the elastic, the acoustic, the anelastic and the visco-acoustic material tensors all have their own material coordinate system, it is here assumed for simplicity and transparency that all properties are given in the same reference coordinate system. The relative alignment of the materials is then constructed as rotations of the reference systems, with respect to the body coordinate axes of the two layers.

2 GOVERNING EQUATIONS

2.1 Anisotropic displacement pressure formulation

A poro-elastic medium consists of an elastic solid containing an interconnected network of pores filled with a viscous fluid. Both the solid and the fluid in the pores are usually considered to be continuous. The porous material is modeled as a homogeneous equivalent solid and a homogeneous equivalent fluid acting and interacting in the same space. The starting points are the early models by Biot [4,5,6] and Biot and Willis [7], the method of modeling foam materials have been developed by e.g. Johnson et al. [18], Allard [1], Allard and Champoux [2] and Pride et al. [23].

Biot extended the isotropic theory of porous material to allow for anisotropic modeling [8] and there is a general awareness that anisotropy may have a significant influence on the acoustic behavior of porous materials [19]. It is also well established that the many parameters used to characterized materials in the Biot-Johnsson-Champoux-Allard model differ in different direction in anisotropic materials [12, 14, 26]. However, the acoustic parameters, such as static viscous permeability and viscous characteristic length, in different directions of an almost transversely isotropic foam do not necessarily line up with the main directions visible in the geometrical sense [25].

The mixed anisotropic displacement pressure formulation underpinning the current work, has recently been proposed by Horlin and Goransson [16] and is a generalization of the weak statement derived by Atalla et al. [3]. It assumes that the material of the solid frame is linearly elastic and isotropic and that the anisotropy of the material is entirely related to the microstructural geometry. A complete description of the model used here is beyond the scope of the present paper, and the interested reader is referred to the work mentioned above. For completeness, a summary of the most important parts will be given.

\[
-C_\omega u^\omega_{ij} - \phi \left( \delta_{ij} + \frac{Q_s}{R} \right) p - \omega^2 \left( \rho_0 \delta_{ij} + \rho_{ij} \rho_{ij}^\omega \right) u^\omega_{ij} - \phi \left( \delta_{ij} \rho^\omega \rho_{ij}^\omega \right) p_j = 0 \quad (1)
\]

\[
-\frac{\phi^\omega}{R} p - \phi \left( \delta_{ij} + \frac{Q_s}{R} \right) u^\omega_{ij} - \frac{\phi}{\omega} \rho_{ij}^\omega \rho_{ij}^\omega + \phi \left( \delta_{ij} \rho^\omega \rho_{ij}^\omega \right) u^\omega_{ij} = 0 \quad (2)
\]

where \( C_\omega \) is the solid frame Hooke's matrix, \( u^\omega_{ij} \) is the solid frame displacement, \( \omega \) is the angular frequency [rad/s], \( \phi \) is the porosity, i.e. the volume fraction of open pore fluid content and \( p \) is the acoustic pore pressure and

\[
R = \frac{\phi^\omega K_{ij}}{1 - \phi - K C_\omega d \phi K / K_{ij}} \quad (3)
\]

\[
Q_s = \frac{1}{1 - \phi - K C_\omega d \phi K / K_{ij}} \quad (4)
\]

where \( K_{ij} \) is the unjacketed frame bulk modulus, \( d \phi \) is the unjacketed compressibility compliance tensor.

As the fluid itself is assumed to be viscous, \( R \) is a scalar quantity, \( K_{ij} \) is obtained using the model by Lafarge et al. [19]. The dilatational coupling \( Q_s \) is however a second order tensor due to the assumed elastic anisotropy.

The equivalent density tensors, \( \rho^\omega_{ij}, \rho^\omega_{ij} \) and \( \rho^\omega_{ij} \), as well as the tortuosity tensor, \( \alpha_s \), are anisotropic generalizations of those used by Allard [1] and may be defined as

\[
\rho^\omega_{ij} = \rho_0 \delta_{ij} + \rho_{ij} - \frac{i}{\omega} b_j \quad (5)
\]

\[
\rho^\omega_{ij} = -\rho_{ij} - \frac{i}{\omega} b_j \quad (6)
\]

\[
\rho^\omega_{ij} = \phi_0 \delta_{ij} + \rho_{ij} - \frac{i}{\omega} b_j \quad (7)
\]

\[
\rho^\omega_{ij} = (\alpha_s - \delta_{ij}) \phi_0 \quad (8)
\]

with \( \rho_0 \) as the ambient fluid density and \( \rho_1 \) as the bulk density of the porous material.

\[
\rho^\omega_{ij} \rho^\omega_{ij} = \delta_{ij} \quad (9)
\]

i.e. \( \rho^\omega_{ij} \) is the inverse of \( \rho^\omega_{ij} \), assuming that the viscous drag tensor, \( b_j \), is invertible [13, 29].

3 ANISOTROPIC FOAM MODELS USED

For the sensitivity study discussed a cellular material was chosen, with orthotropic material symmetry for the three directionally dependent tensors studied here, \( b_j \), \( \alpha_s \) and \( C_\omega \).

In addition, the structural damping related to the solid frame of the porous material is here assumed to be zero. The reason for this choice is that the modeling of the damping of anisotropic materials is still an open issue, especially when it comes to the directivity of the dissipation mechanisms [13]. Therefore, to avoid confusion due to an assumed damping model the damping was omitted in this paper to be relaxed in the presentation given at the conference. Another simplification introduced, without diminishing the value of these preliminary results, is that the viscous characteristic length is assumed to be isotropic although it is, in reality, an anisotropic property. As mentioned before, the knowledge and understanding of anisotropic porous material properties are still limited and often incomplete; therefore simplifications of the description of the materials were felt to be necessary and justified at this stage. On the other hand, should the sensitivities identified with the present model assumptions turn out to be high, this would certainly then add to the future interest for complete and accurate porous material modeling research.
The flow resistivity tensor is taken as transversely isotropic and is given by Eq. (11). The tortuosity was assumed to be orthotropic, Eq. (12).

Note that the principal directions of the static flow resistivity tensors, $\sigma$, and the tortuosity, $\alpha$, are assumed to line up with the principal directions of the solid frame Hooke's matrix, $C$. This is, however, not necessarily the case for all porous materials [22, 28], the consequences of which would be a natural next step to investigate in the current work.

### 3.3 Optimization problem to solve

The basis for the proposed sensitivity analysis approach is to compute maxima and minima of a cost function representing the acoustic response. The acoustic response is calculated using an appropriate simulation model, discussed below, in which the unknown rotations of the constitutive parameters may be varied such that a minimum or a maximum of the acoustic response is found. In the following, the objective function and the constraint functions of the optimization problem are defined.

The cost function was constructed as the acoustic response in a cavity, inherently a function of the different material angles, given by the sound pressure level evaluated in a sub volume of the air cavity connected to the panel, see Figure 1.

![Figure 1. Geometry and subvolume.](image)

The sound pressure square, $p_j^2$, for each evaluated frequency, is calculated as the average of the square sound pressure in a number, $N$, of discrete points in the chosen sub volume, Eq. (16). This quantity was then multiplied with the frequency resolution, $\Delta f_j$, and summed over the entire frequency range, Eq. (15), resulting in a total sound pressure level, $\text{SPL}_t$, which is then subject to minimization or maximization.

\[
(SPL(\alpha_1, \beta_1, \gamma_1, \alpha_2, \beta_2, \gamma_2))_{\omega_n} = 10 \log \left( \sum_{j=1}^{N} \left( p_j^2 \Delta f_j \right) \right) p_j^2
\]

where

\[
p_j = \frac{1}{N} \sum_{n=1}^{N} p_j^2
\]
3.4 Simulation model for anisotropic porous materials in a multilayered configuration

To give a first answer to the question whether the acoustic response of multilayered panels containing anisotropic porous materials may be sensitive to angular changes of material properties or relative angular changes between the two dissipative layers, a numerical model was used to examine the acoustic response of a quadratic panel with aluminum face sheets and two layers of poro-elastic material, elastically bonded to the face sheet where the excitation was applied and separated by a thin air gap from the other aluminum face sheet, see Figure 2.

Figure 2. Layer configuration of the tested panels.

The panel was 0.5 x 0.5 m and excited by a unit force in the z-direction over one element, see Figure 4. The model had homogeneous natural boundary conditions along \( x = 0, x = L_x, y = 0 \) and \( y = L_y \).

The air cavity, in which the acoustic response in Eq. (15) was calculated, was 1.4 m in the z-direction and the subvolume had the dimensions 0.3 x 0.3 x 0.3 m and placed in the middle of the air cavity in the x- and y-direction and 0.2 m from the inner surface of the multilayered panel. To reduce the influence of standing waves phenomena, the inner walls of the air cavity at \( x = 0, y = 0 \) and \( z = L_z \) were assigned a non-frequency-dependent normal surface impedance of \( 257 + 563i \) which implies an absorption factor of about 55 percent. The boundaries of the air cavity at \( x = L_x \) and \( y = L_y \) were considered to be acoustically hard.

It should be noted that the simulation model and the exciting force are academic examples, chosen quite arbitrarily, thus rendering the absolute sound pressure in the air cavity of no particular significance. For this reason, in the discussion of the results from the optimization, merely the differences in sound pressure level between different angular changes of the sound absorbing material will be of interest.

The configuration considered involved an orthotropic foam in two layers of the same material type. The only variations introduced were, the relative orientation of the material properties, which could rotate independently in different directions and thereby possibly achieving different overall dynamic properties considering the direction of the applied excitation, see Figure 4.

The system was solved using a finite element numerical model with hierarchical polynomials of order ranging from 2 to 5 [15]. This was performed for frequency spectra between 100 - 700 Hz with a frequency resolution of 5 Hz.

4 OPTIMIZING THE EULER ANGLES

To evaluate the influence of angular changes in anisotropic porous layers, optimization problem was formulated in terms of the rotations of the anisotropic material properties of the porous layers, using Euler angles with Z-Y-X fixed axis rotation. For details of the matrices used for these transformation, see [9].

As the two porous layers could rotate independently of each other six Euler angles were needed as design variables and the summed SPL, Eq. (15) was used as the objective function. This objective function was both minimized and maximized in order to estimate the possible difference between a worst case and a best case scenario.

Five different starting points for the minimization process were used, see Table 2 and, based on the result in those starting points, two different starting points were selected for the maximization. It should, however, be pointed out that this analysis cannot be expected to guarantee that the global minimum or maximum has been found. As the objective of the current work was to investigate the sensitivity associated with the orientation of anisotropic porous materials, it does nevertheless indicate to what degree the problem is convex and in addition provide some useful information about the differences between different minima or maxima both in terms of the chosen objective function but also in the resulting Euler angles. And most importantly, it does provide a first estimation of possible differences in acoustic response that may be caused by angular changes of anisotropic acoustic porous materials.

The objective of the present paper is not to find the global minimum or maximum of the stated cost function, but to evaluate the sensitivity to the orientation of anisotropic materials in a general sense. To illustrate the behavior of the cost function, Eq. (15), the value at starting point 1, Table 2, was used as a reference against which the minima and maxima found were evaluated. As this cost function result involved no angular changes it was considered to be adequate as a reference case, the choice of reference case admittedly of
a somewhat arbitrary nature. Fortunately it does not affect the outcome of the present analysis as the most interesting evaluations are made mainly between the maximization and minimization.

Figure 4. Model with load.

4.1 Results and discussion

As the present study of the acoustic behavior of anisotropic porous materials is based on a forced response simulation model, there are two aspects of the results that should be pointed out before going through the outcome of the optimizations performed. First, as a non-symmetric, localized excitation was used, see Figure 4, both the global and the relative orientation of the two layers could be expected to be biased by this and in some sense removing a certain level of generality in the results. However, despite this the relative orientation of the material properties of the two layers should on the other hand provide a more general picture of the sensitivity of response as a function of the orientation.

Table 2. Starting points used in minimizations.

<table>
<thead>
<tr>
<th>Start Point values</th>
<th>Euler angles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Layer 1</td>
</tr>
<tr>
<td>1</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.5, 0.5, 0.5</td>
</tr>
<tr>
<td>3</td>
<td>-0.5, -0.5, -0.5</td>
</tr>
<tr>
<td>4</td>
<td>0.5, 0.5, 0.5</td>
</tr>
<tr>
<td>5</td>
<td>-0.5, -0.5, -0.5</td>
</tr>
</tbody>
</table>

For these reasons the results from the optimization analysis are presented in terms of the actual rotations pertaining to minima and maxima found as well as to the corresponding FRFs. Due to the difficulties of showing 3D rotations in a comprehensible way in printable graphs, several different ways of illustrating the results are given below.

Table 3. SPL difference for optima vs [0 0 0] results.

<table>
<thead>
<tr>
<th>Start Point values</th>
<th>Min/Max Euler angles</th>
<th>Difference in dB [SPL]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Layer 1</td>
<td>Layer 2</td>
</tr>
<tr>
<td>Minima</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>A1</td>
<td>0.45, 0.41, -0.25</td>
</tr>
<tr>
<td>2</td>
<td>A2</td>
<td>0.38, 0.40, -0.25</td>
</tr>
<tr>
<td>3</td>
<td>A3</td>
<td>-1.46, 0.39, -0.20</td>
</tr>
<tr>
<td>4</td>
<td>A4</td>
<td>1.40, 0.36, -0.21</td>
</tr>
<tr>
<td>5</td>
<td>A5</td>
<td>1.40, 0.36, -0.21</td>
</tr>
<tr>
<td>Maxima</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>A6</td>
<td>0.45, -1.28, -0.65</td>
</tr>
<tr>
<td>4</td>
<td>A7</td>
<td>1.28, 1.06, 1.58</td>
</tr>
</tbody>
</table>

From Table 3 it is clear that a comparison of the minima and the maxima gives a level difference, between the best case and the worst case found, of 4.6 dB. The rotation of material properties compared to the global coordinate system may be found in Figure 5 through Figure 10, where the x- and y-axes are plotted in both positive and negative direction, as a 180° rotation around the material z-axis would have no influence of the physical material behavior.

Looking at the results, it may be seen that minima A1, A2 and A5 all had similar material property rotations in layer 1, Figure 5, and similar in z-direction but with a small deviation of the rotation of the x-y-plane in layer 2, Figure 6.

Figure 5. Rotation of material property axes in layer 1 for the different minima compared to [0 0 0]-rotation, z-axis=black dashed, y-axis=black dashed, x-axis=red solid. A1= , A2=x A5=diamond.

Figure 6. Rotation of material property axes in layer 2 for the different minima compared to [0 0 0]-rotation, z-axis=blue dotted, y-axis=black dashed, x-axis=red solid. A1= , A2=x A5=diamond.

Minima A3 and A4 both had very similar property rotations in layer 1, Figure 7, and similar although not exactly the same in layer 2, Figure 8.

Figure 7. Rotation of material property axes in layer 1 for the different minima compared to [0 0 0]-rotation, z-axis=blue dotted, y-axis=black dashed, x-axis=red solid. A3=triangle, A4=square.
Figure 8. Rotation of material property axes in layer 2 for the different minima compared to [0 0 0]-rotation, z-axis=blue dotted, y-axis=black dashed, x-axis=red solid. A3=triangle A4=square.

Comparing the two maxima the rotations were the same in layer 2, with the only difference being that the z-axes were pointing in opposite directions, Figure 9, which does not influence the physical behavior of the orthotropic porous material.

This shows that even though there were some constraints put on the design variables the same material angles can be described with different Euler angles and therefore some minima or maxima may actually be closer than they appear when comparing the numerical values of the resulting optimal angles. In addition, the material rotations of layer 1 for the two maxima showed some similarities but were not exactly the same, Figure 10. An interesting observation is also that for the minima found the z-axis of layer 1 is rotated slightly off the body coordinate z-axis, while for the two maxima the z-axis is rotated almost 90 degrees.

Figure 9. Rotation of material property axes in layer 1 for the different maxima compared to [0 0 0]-rotation, z-axis=blue dotted, y-axis=black dashed, x-axis=red solid. A6=diamond A7=square.

Figure 10. Rotation of material property axes in layer 2 for the different maxima compared to [0 0 0]-rotation, z-axis=blue dotted, y-axis=black dashed, x-axis=red solid. A6=diamond A7=square.

This observation also holds for the two maxima. Another interesting observation that may be made from the FRFs is that the main improvement in total SPL of the minima compared to the maxima is due to the lower part of the studied frequency range.

Figure 11. FRF of the different maxima and minima found compared to [0 0 0]-rotation which is shown as blue dotted. A1=blue solid, A2=black solid, A3=red solid, A4=green solid, A5=magenta solid, A6=magenta dashed, A7=green dashed.

The two maximization solutions found are clearly above the minimization solutions for frequencies below 250 Hz and at the same time well below for higher frequencies. At the same time all minima found are below the [0 0 0]-rotation response curve, except for frequencies below 150 Hz.

5 DISCUSSION

As a general observation, the min-max searches for both materials verified the importance of the anisotropy as well as the influence of material alignment for such materials. This was manifested through a clear change in acoustic response due to angular changes of the investigated anisotropic materials. Some seemingly different minima found turned out to be rather close to other minima. In general the different minima and maxima did not appear to be scattered all over the design space, on the contrary; there seemed to be different regions within the range of angles permitted in which several minima could be found and other distinctly separated regions containing maxima. This may indicate that there are regions...
of local minima or maxima in the vicinity of some specific Euler angles.

When looking at the frequency response functions pertaining to the different minima and maxima, Figure 11, it is apparent that the improvement of total SPL is due to improvements in the low frequency region, whereas for frequencies above 250 Hz there is no improvement, in fact, quite the opposite; the maximizations A6 and A7 show lower SPL for frequencies above 250 Hz. This type of trade off between different frequency regions is not uncommon when optimizing acoustic properties [20]. However comparing the FRFs of the minima with that of the 0 0 0-rotation an improvement, though small, is visible over almost the entire frequency range. This shows that an optimization of acoustic properties does not always need to be a trade off between different frequency ranges.

Focusing on the sensitivity related to the orientation of the material properties, it was observed during the optimization process that, when approaching a minimum the changes in objective function were very small compared to the changes in design variables i.e. the objective function converged significantly faster than the design variables. This suggests that the solutions found, i.e. the resulting SPL, around the minima were quite unaffected by small angular changes. This also had the effect that the optimization was sometimes terminated before the Euler angles were quite converged and the resulting optimized angles may be considered to have an accuracy of about ~0.005 rad. This accuracy should however be regarded with some caution. As the design variables were not totally converged in some cases and the fact that changing one of them may induce the others to change too there is always a risk, however small, that the optimized design variables would chance dramatically if yet more iterations were allowed.

Regarding the relative orientation of the material properties axes of porous layer 1 and 2 the results are however inconclusive. Intuitively the relative layer orientation should represent one of many important factors in multilayered configurations, this also seems to be the case for the panel containing orthotropic material.

6 CONCLUDING REMARKS

For the material studied the changes in cost function were very small towards the end of the optimization process while the angular changes where still visible, thus rendering the extremal points rather insensitive to small angular changes close to the extremal points. A consequence of this is that the optimal angles for each local minima might not have reached their final value and could differ slightly if the optimization process was allowed to continue for additional iterations.

Whereas the difference between the maximum SPL and the minimum SPL was significant the difference in SPL between individual minima was quite small. All minima found had a resulting SPL, within 0.2 dB, even if they were found at quite different Euler angles. In addition the small difference in FRF between different minima and the apparent tendency to appear in a limited number of minima regions may indicate that once the regions of local minima and maxima have been found, the exact Euler angles are less important, as long as the material angles stay within a minima region and thus avoid maxima regions. For practical applications this would probably be a quite compelling physical feature.

Studying the frequency response functions, Figure 11, it is quite obvious that the improvement in SPL is restricted to frequencies around 200 Hz, substantially improving the SPL at those frequencies at the expense of the SPL at higher frequencies. If the frequency range of interest was altered and thus excluding frequencies below for example 250 Hz the outcome of the optimization would doubtlessly be totally different. A weighting function applied to the FRF or other extensions or limitations of the frequency range would also influence the result. Obviously, a proper choice of objective function and frequency range of interest is therefore of utmost importance to achieve a useful result in practical applications.

Finally one can conclude that there are significant possibilities of improvement in practical applications connected with angular modification of anisotropic material properties of acoustic absorbents. Such improvement can according to the numerical simulations be achieved within an existing acoustic panel using readily available porous material without adding extra weight or volume. However, the knowledge of anisotropic material properties, including their principal directions as well as their structural losses and other damping behavior is today very limited, making anisotropic porous acoustic materials an important area well deserving further research.

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