Modeling and optimization of a dual density lightweight acoustic material

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ABSTRACT
Lightweight acoustic materials (also known as dual density insulators) are being more and more widely used in vehicle sound package application, while their predictive modeling and optimization have been a challenge. A type of lightweight material with dual density felt-membrane-felt configuration is studied in this paper. The acoustic performance modeling and influencing factors of the material are discussed. A multi-variable optimization procedure for this lightweight material configuration was established using ViNAS software, which is based on acoustic transfer matrix method (TMM) in the context of Biot theory and surrogate modeling optimization techniques. The model predictions agree reasonably well with testing data for this type of material, which can be used in the development of lightweight dash inner, floor carpet, etc. Based on this model, the acoustical performance of the material can be optimized to meet vehicle acoustical requirements.

Keywords: material, modeling, optimization

I-INCE Classification of Subjects Number(s): 76.9

1. INTRODUCTION
The high pressure on reducing fuel consumption and CO₂ emission in automotive industry leads to weight reduction requirement for all parts of a vehicle. For interior trim, the design of sound package faces the same challenge. Traditional interior trim such as a typical dash that is made up of a barrier (EVA or PVC) layer and a decoupler layer (foam or felt) has a high sound transmission loss (STL), but with a relatively heavy mass. In recent years, several lightweight acoustic material alternatives to conventional vehicle interior trims have been proposed and put into production (1, 2, 3). The common principle behind the development of this structure is to utilize absorption performance to compensate for the diminished transmission loss (or insertion loss) performance due to the lower mass. The most typical application is dual density insulators.

Felt-membrane-felt structure is a type of dual density insulators. In the process of designing this material, it’s found that the correlation between testing data and prediction results by existing simulation software is a big challenge. Tian et al (4) investigated the normal incidence sound absorption coefficient and sound transmission loss of a felt-membrane-felt material using different modeling methods. The results calculated using both the micro perforated membrane theory and Biot theory didn’t match the measured data very well. Alexander et al (5) showed that when a layer of impervious membrane is added to a felt surface, the predicted transmission loss will be different from measurement at high frequencies. The material model in some widely used tools doesn’t perform well for this type of lightweight acoustic material. This leads to difficulties in optimizing the parameters of this type of material and discovering the best balance of transmission loss and absorption performance.

Therefore, we further investigated this problem and performed model simulation using a newly
developed software called ViNAS, which is based on acoustic transfer matrix method in the context of Biot theory, combined with surrogate modeling optimization techniques.

2. THEORY

2.1 Transfer Matrix Method

Acoustic transfer matrix method (TMM) in the context of Biot theory (6) is used in ViNAS software for multi-layer porous material. Figure 1 shows a plane acoustic wave impinging on a material with thickness $h$ at an incidence angle $\theta$. The geometry of the problem is in the $(x_1, x_3)$ plane. Several types of wave can propagate in the material, according to their nature. The $x_1$ component of the wave number for each wave propagating in the finite medium is

$$k_j = k \sin(\theta)$$

where $k$ is the wave number in free air. Sound propagation in each layer is represented by a transfer matrix $[T]$ such that

$$V(M) = [T]V(M')$$

where points $M$ and $M'$ are close to the forward and the backward face of the layer, respectively. The components of the vector $V(M)$ are the variables that describe the acoustic field at a point $M$ of the medium. The matrix $[T]$ depends on the physical properties of each medium.

![Figure 1 – Plane wave impinging on a domain of thickness $h$.](image)

The acoustic field in the porous layer consists of six waves. The six acoustic quantities that have been chosen are three velocity components and three elements of the stress tensors: the two velocity components $v_{1}^s$ and $v_{3}^s$ of the frame, the velocity component $v_{3}^f$ of the fluid, the two components $\sigma_{33}^s$ and $\sigma_{13}^s$ of the stress tensor of the frame, and $\sigma_{33}^f$ in the fluid. If these six quantities are known at a point $M$ in the layer, the acoustic field can be predicted everywhere in the layer. Moreover, the values of these quantities anywhere in the layer depend linearly on the values of these quantities at $M$. Let $v^p(M)$ be the vector

$$v^p(M) = \begin{bmatrix} v_{1}^s(M) & v_{3}^s(M) & v_{3}^f(M) & \sigma_{33}^s(M) & \sigma_{13}^s(M) & \sigma_{33}^f(M) \end{bmatrix}^T$$

The transfer matrices of each layer were evaluated. Then we apply the continuity conditions between two adjacent layers of different nature. Figure 2 shows a stratified medium, where two points $M_{2k}$ and $M_{2k+1}$ ($k=1, n-1$) are close to each other at each side of a boundary between layers ($k$) and ($k+1$). An interface matrix, which depends on the nature of the two layers, must be used to relate the acoustic field vectors $V^{k}$ ($M_{2k}$) and $V^{k+1}$ ($M_{2k+1}$). For simplification, the interface matrices are derived for the two first layers of Figure 2.
In this case, the global transfer matrix \([T^p]\) is written as:

\[
[T^p] = [T_{1}^p][I_{pp}][T_{2}^p]
\]

(4)

where \([I_{pp}]\) is the intermediate matrix reflecting the boundary conditions between adjacent layers.

### 2.2 Optimization and Design of Experiments (DoE)

The surrogate model optimization techniques are implemented in ViNAS. The accuracy of surrogate model depends on number and distribution of samples in the design space. The choice of location of the samples is important to get a good approximation model, especially when evaluations (experiment or simulation) are expensive. A special multidimensional distribution generating method is applied in ViNAS.

In order to control the computational cost of the whole design process, a special basis function surrogate model method is employed to build the surrogate model of the material. The parameters of the material are defined by a group of design variables. In this case, the number of total design parameter for the material is set to be a certain number.

For this method, it uses linear combination of symmetric functions based on Euclidean distance to establish approximation models, and its approximation fits well to the arbitrary contours of both deterministic and stochastic response functions. A simple form of radial basis function can be expressed as:

\[
f(x) = \sum_{i=1}^{p} w_i \varphi(r_i) = w^T \varphi
\]

(5)

where \(w = [w_1, w_2, \ldots, w_p]^T\), \(w_i\) is weight coefficient, \(\varphi = [\varphi(r_1), \varphi(r_2), \ldots, \varphi(r_p)]^T\), and \(r_i = \|x - x_i\|\) is Euclidean distance between point \(x\) and sample point \(x_i\).

The predictive model should satisfy the following interpolation conditions:

\[
f(x_i) = y_i (i = 1, \ldots, p)
\]

(6)

The Multi-Quadric function is chosen in this method, which has extensive estimated characteristics. The MQ function form can be expressed as:

\[
\varphi(r) = (r^2 + d^2)^{0.5} \quad (d \geq 0)
\]

(7)
3. MEASUREMENT, PREDICTION AND OPTIMIZATION

3.1 Material Composition and Parameters

Table 1 shows the composition of the multilayer lightweight insulator. Felt-1 is the layer facing air and Felt-2 is the layer facing panel. These three layers were put together, heated and mold-pressed to a 15mm flat stock.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Surface density, g/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Felt-1</td>
<td>910</td>
</tr>
<tr>
<td>Membrane</td>
<td>60</td>
</tr>
<tr>
<td>Felt-2</td>
<td>450</td>
</tr>
</tbody>
</table>

Table 2 shows the parameters of the two porous layers. The first three parameters were measured while the last three were derived according to the impedance tube measurement data. It’s not practical to tear down the multilayer and measure each layer because the felt could be out of shape and even broken. The samples from which we got these parameters were made separately. For each layer, the same raw material was mold to the same thickness as in the multilayer.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Density kg/m³</th>
<th>Porosity</th>
<th>Airflow resistivity N/m³.s</th>
<th>Tortuosity m</th>
<th>Viscous c.l</th>
<th>Thermal c.l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Felt-1</td>
<td>90.00</td>
<td>0.950</td>
<td>44833</td>
<td>1</td>
<td>derived</td>
<td>derived</td>
</tr>
<tr>
<td>Felt-2</td>
<td>120.25</td>
<td>0.934</td>
<td>106261</td>
<td>1</td>
<td>derived</td>
<td>derived</td>
</tr>
</tbody>
</table>

3.2 Preliminary Design and Optimization

In the preliminary design and optimization phase we kept the total thickness of the material unchanged and varied the parameters that can be tuned in reality. Model simulation was performed using a newly developed software called ViNAS. ViNAS has an Acoustic Material (AM) module that is based on acoustic transfer matrix method in the context of Biot theory, combined with surrogate modeling optimization techniques.

Figure 3 and 4 show the starting baseline material simulation results, the preliminary design targets, and the optimized results. After a series of optimization steps, the optimized material has much better performance than the starting baseline.

In the optimization process, we defined a distance-to-target indicator. The lower value of the indicator means closer to the target. From Figure 5 one can see that the indicator for absorption drops quicker (converges faster) than the indicator for STL. After about 160 cases run, both indicators drop to a reasonable value, thus the optimization process was stopped. However, the material can be further optimized if more were run, in order to meet more aggressive targets.
Figure 3 – Optimization of the material absorption by ViNAS

Figure 4 – Optimization of the material STL by ViNAS
3.3 Measurements and Test-model Correlation

The random incidence absorption coefficient and transmission loss were measured in standard acoustic labs at Tuopu. The absorption measurement was taken in a reverberation room of 100m³ volume with 7.2m² samples. For the transmission loss measurement, a 0.8mm thick steel panel was clipped on the window frame between anechoic room and reverberation room. A square sample of 0.5m×0.5m was mounted on the panel. In both absorption and transmission loss measurements, the edges of the sample were sealed to avoid sound leakage.

The initial calculation was based on TMM theory and carried out through existing commercial software, where the felt layer was modeled as limp porous material and its major parameters are listed in Table 2, and the membrane was modeled as a limp, impervious screen and density is the only parameter.

As shown in Figure 6 and 7, the correlation between the model prediction by ViNAS and measured data was reasonably good, and showed significant improvement comparing to the initial correlation results from other existing software. ViNAS-AM module has built-in membrane and felt material types, taking account of their boundary conditions and special characteristics. A multi-variable, multi-step optimization process was conducted within the ViNAS-AM module.
4. CONCLUSION

A lightweight acoustic material with felt-membrane-felt configuration was successfully designed, optimized, produced, and tested at Tuopu.

The correlation between measurement and model prediction by ViNAS Acoustic Material (AM) Module was reasonably good for both absorption and transmission loss. A multi-variable optimization procedure for
lightweight acoustic material was established using ViNAS software, which is based on acoustic transfer matrix method in the context of Biot theory and surrogate modeling optimization techniques. It’s useful for the development of lightweight sound package parts such as dash inner, floor carpet, etc. Based on this procedure, the acoustical performance of the material can be optimized to meet vehicle acoustical requirements.

REFERENCES