

Prediction of Biot Properties for Describing Fibrous Materials in SEA Models

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ABSTRACT

SEA models are used to predict the performance of acoustic packages when assessing the performance of vehicle level or body noise reduction targets. One of the challenges faced by CAE engineers is the ability to estimate the performance of different materials used in the sound package at the design stage. Analysts can use measured data in the form of insertion loss and random incidence absorption if available or can predict the performance of materials using a Biot type description. The use of the full poro-elastic Biot model for materials requires knowledge of the fluid and elastic properties, however a limp or rigid model can be used to describe the material based only on the fluid properties and this is often sufficient to describe fibrous materials.

In this paper a method will be outlined which will allow the material properties of fibrous materials to be estimated from basic normal incidence data that is provided by material suppliers. This approach will then allow the effect of compression on the material properties to be predicted and the impact on the acoustic performance to be estimated. In addition it will allow the analyst to estimate the effects of increasing or reducing the fiber weight. Predictions will be compared with measured data.

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INTRODUCTION

SEA modeling of vehicles is used extensively in the global automotive industry to predict the interior acoustic levels of passenger vehicles. The first task in building a vehicle SEA [1] model is creating the vehicle structure which is divided into plate and shell subsystems, where a subsystem is defined as a group of resonant modes of a similar type that store energy. The second task is partitioning the interior and exterior air spaces into SEA acoustic cavities to diffuse energy through the model. The subsystem energy can be converted to a variable such as average sound pressure level for acoustic spaces or vibration level for plates and shells. For airborne noise due to powertrain, tires and exhaust, the SEA model can be used to predict the absolute sound pressure levels or body noise reduction (NR) in the frequency range from 315 Hz to 10 kHz. The first application of SEA in the automotive industry was by DeJong [2] and Moeller and Powell [3] reviewed the subsequent development of SEA in the automotive industry. Work has focused primarily on the development SEA load cases [4] and full vehicle models e.g. mid-sized sedan [5], minivan [6], light truck [7].

After the basic vehicle structure and acoustic spaces have been created the next challenge facing the CAE engineer is

the modeling of the sound package components applied to the exterior and interior of the vehicle. Decisions are made regarding the sound package from the SEA models before prototype vehicles are available for testing, therefore it's important to have an accurate representation of the trim materials. This is important as sound package studies involve determining the impact of surrendering packaging space for noise control treatments to accommodate other components. For fiber materials this can involve changing the tooling to compress the fibrous materials. For sound package modeling, the question of how to model these changes this has often been a difficult question to answer. In this paper, a process is outlined for the modeling of fiber based materials, determining the Biot properties and estimating the effects of thickness variation for vehicles and component models.

SOUND PACKAGE

One of the principal functions of an SEA model is to assess the performance of the vehicle sound package and optimize the deployment of interior and exterior acoustic materials, for NVH performance, mass and cost. SEA models can model trim components by two different approaches. The simplest approach is to use measured data in the form of

insertion loss and random incidence sound absorption from component testing or measurements on flat samples per SAE J1400 [8] or ASTM C423[9]. The alternative approach is to use analytical models to predict the performance of NVH components utilizing the transfer matrix method (TMM).

TMM is based on the representation of plane wave propagation in different media in terms of transfer matrices and allows for multi-layers made up from combinations of elastic, porous-elastic and fluid layers. In a given layer, sound propagation is represented by a transfer matrix [T] such that $V(M1) = [T] V(M2)$, where M1 and M2 are two points set close to the forward and backward face of the layer, respectively, and where the components of the vector $V(M)$ are the variables which describe the acoustic field in a point M of the medium. Using continuity equations at different interfaces and the impedance equations in the source and receiving domains which are assumed to be semi-infinite, a global system of equations is formed and solved for the reflection and transmission coefficients.

To describe the properties of the porous layers, a Biot description is used, and there are three models that can be used, a porous limp, porous rigid and porous elastic model. Allard and Atalla [10] and Brouard et al [11] provide a comprehensive theoretical review of the Biot theory and the detailed theory of different material models. The properties required for the different material types are shown in Figure 1.

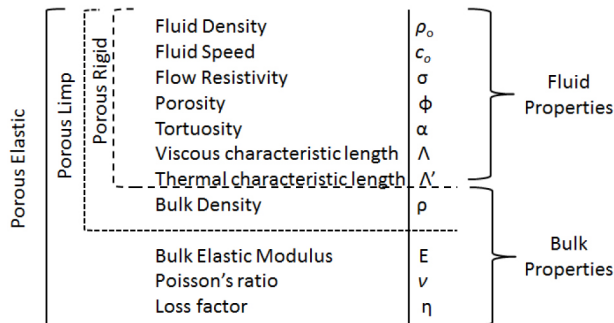


Figure 1. Biot properties required for different poro-elastic material models

In this paper we are concerned with the modeling of fiber materials therefore the discussion is restricted to materials that can be classified as porous limp or porous rigid which are defined by the equivalent fluid properties. This paper does not consider porous elastic models therefore the elastic bulk properties are not included in the following discussion. For some materials the elastic properties can be very important, particularly for transmission loss prediction, however predicting the elastic modulus of fiber based materials is very difficult to do and usually requires a measurement with a dynamic mechanical analyzer to obtain this property. In most vehicles, porous materials are used in absorption materials, carpet systems, dash insulators, headliners etc., and are manufactured from combinations of fibrous materials or foam

materials. One of the challenges is building a description of the sound package to be used in an SEA model and this paper proposes the use of published models by Tarnow [12] to predict the airflow resistance of fibrous materials and to estimate the effect of compression on the fibrous materials.

TARNOW MODELS

For porous limp and porous rigid materials, a Biot description requires the following parameters: airflow resistivity (σ); porosity (ϕ); tortuosity (α), and viscous and thermal characteristic lengths (Λ , Λ'). The viscous and thermal characteristic lengths are related to the other properties by equation (1) as given by [9].

$$\Lambda = \left(\frac{8\eta\alpha}{\sigma\phi} \right)^{0.5} \frac{1}{c} \quad \Lambda' = \left(\frac{8\eta\alpha}{\sigma\phi} \right)^{0.5} \frac{1}{c'} \quad (1)$$

Where η is the dynamic viscosity and c and c' are parameters related to the pore shape and $c \leq c'$.

In the work published by Tarnow [11], models were proposed to allow the prediction of airflow resistance for two different fiber layups, square lattice and a random lattice of fibers as shown in Figures 2 and 3. In the method developed by Tarnow, a method of calculating the airflow resistivity for regularly and randomly spaced fibers was developed based on an approach using Voronoi polygons. This allowed explicit relations to be developed for airflow resistivity based on the mean fiber spacing (b), fiber diameters ($2a$) and the properties of air.

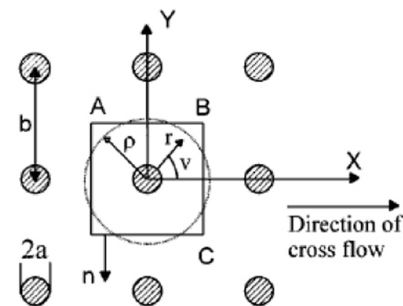


Figure 2. Tarnow[12] square lattice model

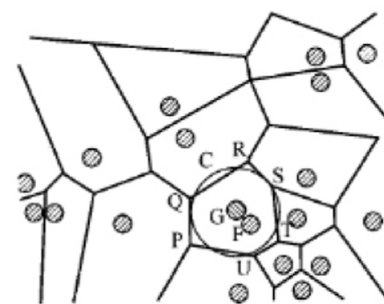


Figure 3. Tarnow[12] Random lattice model

The Tarnow equations for square and random lattice arrangements for different airflow directions are given in [equations \(2\),\(3\),\(4\),\(5\)](#) for different fiber and lattice orientations.

1. Square lattice, flow direction perpendicular to the orientation of the fibers

$$\sigma_{ls} = \frac{4\pi\eta}{b^2 \left[\ln\left(\frac{1}{d}\right) - \frac{3}{2} + 2d \right]} \quad (2)$$

2. Square lattice, flow direction parallel to the orientation of the fibers;

$$\sigma_{cs} = \frac{4\pi\eta}{b^2 \left[\ln\left(d^{-\frac{1}{2}}\right) - \frac{3}{4} + d - \frac{1}{4}d^2 \right]} \quad (3)$$

3. Randomly oriented fiber lattice, flow direction perpendicular to the orientation of the fibers;

$$\sigma_{lr} = \frac{4\pi\eta}{b^2 \left[1.28 \ln\left(\frac{1}{d}\right) + 2d - 1.474 \right]} \quad (4)$$

4. Randomly oriented fiber lattice, flow direction parallel to the orientation of the fibers

$$\sigma_{cr} = \frac{4\pi\eta}{b^2 \left[0.64 \ln\left(\frac{1}{d}\right) - 0.737 + d \right]} \quad (5)$$

For most fiber materials in automotive applications, models described by [equations \(2\)](#) and [\(4\)](#) can be used. There are some materials that use vertically lapped fibers for porous layers and therefore [equations \(3\)](#) and [\(5\)](#) would be used to describe the material. To use [equations \(2\),\(3\),\(4\),\(5\)](#) it is therefore necessary to calculate the fiber radius (a), the fiber spacing (b) and the volume concentration of the fibers.

For engineered fibers, the density material and denier (den) of the fiber are can be used to estimate the fiber radius. Denier is defined as the mass in grams per 9,000 meters of a single fiber strand. The denier is based on a natural standard-i.e., a single strand of silk is approximately one denier. A 9,000-meter strand of silk weighs about one gram. A *microdenier* fiber is used to describe filaments that weigh less than one gram per 9,000 meters. The fiber radius (a) can be calculated from the denier and fiber density from [equation \(6\)](#).

$$a = \sqrt{\frac{0.001 \times \text{den}}{9000 \pi \rho_{\text{fiber}}}} \quad (6)$$

Knowing the fiber radius the volume concentration (d) of the fibers can be calculated from [equation \(7\)](#),

$$d = \pi \frac{a^2}{b^2} \quad (7)$$

The term (b) is the mean spacing or square root of the area per fiber and is given by,

$$b = \sqrt{\frac{\pi a^2}{d}} \quad (8)$$

Calculation of the fiber concentration d then allows the porosity ϕ of the fiber layer which can be calculated from [equation \(9\)](#),

$$\phi = 1 - d \quad (9)$$

The tortuosity (α) of the sample can be estimated from [equation \(10\)](#) which is based on the author's experience.

$$\alpha = \left[\frac{1}{\phi^2} \right] \quad (10)$$

The combination of [equations \(1\), \(2\), \(3\), \(4\), \(5\), \(6\), \(7\), \(8\), \(9\), \(10\)](#) provides a system of equations for estimating the Biot properties based on some basic knowledge of the fiber properties.

APPLICATIONS

Having outlined the system of equations based on the Tarnow equations, there are two major applications where these can be used to characterize fiber materials in vehicle and component SEA models.

(a). Prediction of Biot properties for fiber based materials and compressed properties.

(b). Estimating average fiber properties for samples and parts based off airflow or impedance tube test data.

These applications are discussed in the following sections:

Example 1. - Glass Fiber Prediction

For quick estimate of properties, [equations \(1\), \(2\), \(3\), \(4\), \(5\), \(6\), \(7\), \(8\), \(9\), \(10\)](#) can be used in an Excel spreadsheet or Matlab, to estimate the properties. The data input can be set so that different fiber types and densities can be selected. Since fiber based materials are often specified in terms of surface density (g/ft^2 or g/m^2), this is held as a constant, and the layer density calculated for different thicknesses. [Table 1](#) shows an example of the estimated Biot properties for 100 g/ft^2 10 denier glass fiber from 25-mm thickness to 2.5 mm thickness.