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A NOVEL ALGORITHM FOR ESTIMATING BIOT PARAMETERS IN ACOUSTIC SIMULATION OF FIBROUS MATERIALS BASED ON RAW MATERIAL COMPOSITION

Minh-Tan Hoang [1*] **Massimiliano Tiengo** [2] **Evan Harry** [2]

[1] Adler Pelzer Group, Acoustic TechCenter R&D, Z.I. François Sommer – BP13, 08210 Mouzon, France

[2] Adler Pelzer Group, C.so Savona 45, I 10029 Villastellone, Italy

ABSTRACT

For an automotive trim supplier, the production of material and component samples for certification and acceptance by vehicle manufacturers is an expensive and time-consuming task. Circumventing the need for these via pure simulation still requires the correct determination of Biot parameters, which can be carried out via batch samples. However, this is a complex task that is sensitive to both the measurement and the condition of the samples. Any discrepancies will propagate through the simulation and will create uncertainties in the results.

This paper describes a novel approach, called *Genetic*, in which the empirical calculation of Biot parameters of fibrous composites is based purely on the blended mixture of fibre types. This technique was the culmination of an extensive measurement and characterisation campaign on a wide selection of fibre types and is part of an ongoing investigation into the use of data science applications to enhance internal methodologies.

The next phase of the project is focused on porous media such as foams.

Keywords: *fibrous materials, fineness, composition, transport parameters, acoustic simulation, absorption, transmission loss.*

[*] ***Corresponding author***: minh-tan.hoang@adlerpelzer.com.

1. INTRODUCTION

Fibrous materials are increasingly used in automotive NVH (Noise, Vibration, and Harshness) packages due to their effective absorption and insulation properties. Their adoption by OEMs is also driven by sustainability concerns, such as the integration of recycled PET fibers. However, optimizing their acoustic performance requires a precise understanding of their physical properties, commonly referred to as Biot parameters. These parameters are divided into two groups: (i) transport parameters of an equivalent fluid model (e.g., JCA or JCAL), governing viscous and thermal dissipation within porous media, and (ii) solid-phase elastic parameters, which are more relevant for structural interactions but less critical for absorption-related applications [1].

As an automotive NVH trim supplier, it is essential to have access to accurate material properties, not only the Biot parameters but also key acoustic performance metrics such as normal incidence absorption, diffuse field absorption, and transmission loss of flat (planar) samples. These properties are crucial for material selection, simulation and validation. In practice, they are particularly relevant in (i) Request for Quotation (RFQ) phases to ensure compliance with OEM constraints (e.g., thickness, weight); (ii) acoustic simulations, for improved numerical models; and (iii) manufacturing and innovation, guiding material validation and optimization.

Currently, material properties of flat samples are obtained through two primary strategies:

- Material databases: These databases compile data for flat samples of various thicknesses (e.g., 5 to 30 mm), including Biot parameters, normal incidence and diffuse field absorption, as well as transmission loss. However, this approach is constrained by predefined thicknesses and material types, requiring large-scale material manufacturing and extensive experimental campaigns, making it a less efficient solution.

- Acoustic simulation: Which are based on characterized Biot parameters for a given material composition. While simulations offer a way to estimate material performance, uncertainties may arise due to variations in sample conditions, material characterization methods, and acoustic models. These can be mitigated by validating simulation results against experimental data.

A more elegant approach is to estimate the so called composite "acoustic transport parameters" directly from fundamental raw material characteristics, such as fiber radius (µm) or fineness (dTex, mass in grams per 10 km of fiber), together with composition ratios, thereby enabling a predictive framework that reduces the dependency on costly experimental measurements.

Several methods have been proposed for computing the transport parameters of fibrous media from fiber properties. Publications relating to this computation are listed in the references [2] to [8] but can be categorized into:

- **Empirical regression models** – deriving parameters from experimental datasets (e.g., Biboud et *al.* (2024) on nylon fibers [4].
- **Analytical (or geometrical) models** – developing theoretical formulations based on fiber structures [5]-[6].
- **Hybrid numerical/semi-analytical models** – identifying transport parameters that best fit numerical simulations data [3].
- **Compression-based estimation models** – considering the effect of compression on initial material properties [7].

Pompoli and Bonfiglio [2] adapted existing analytical formulations and validated them through numerical simulations for parallel fiber structures. However, these formulations require the effective radius of the fibrous raw materials, which are typically not provided in manufacturing material data sheets. Santoni et *al.* [8] further utilized these formulations to study recycled fiber mixtures, but they required airflow resistivity and porosity of loose fibers as input parameters to inversely determine the effective radius of each kind of fiber in the composition.

While previous studies primarily focus on validating transport parameter estimations against normal incidence absorption measurements, automotive applications require a broader scope. Diffuse field absorption is an important parameter that must be considered for real-world applications.

In this paper, we propose a novel algorithm, developed through an extensive experimental campaign, to estimate JCA parameters from known manufacturing parameters: fineness in dTex and composition ratios. This algorithm provides reliable input data for simulating impedance tube absorption, diffuse field absorption, and sound transmission loss across a wide range of fibrous material densities and compositions.

Section (2) describes the materials and methods used, including fiber compositions and experimental approaches. Section (3) presents the results, validating the *Genetic* algorithms through various acoustic measurements. Finally, Section (4) concludes the paper, highlighting the practical applications of the proposed methods.

2. MATERIAL AND METHODS

2.1 Fiber Material

A group of fibrous flat samples were studied, each composed from five different mixtures. Each mixture consisted of a fixed number of fiber types with corresponding mass participation ratios. The raw loose fibers were classified as: PET (polyethylene terephthalate), Cotton fibers and PET-CoPET bicomponent fibers, where the core was PET and the surface was CoPET in a 1:1 ratio. The fineness of the input raw materials, expressed in dTex, was also known.

The fiber mixture compositions were selected based on several factors, including acoustic performance, mechanical requirements, processing constraints and cost. The chosen materials spanned a wide range of fiber fineness, with a variation factor of approximately 40 between the finest and coarsest fibers, depending on the mixture.

For each mixture, flat samples were fabricated with varying thicknesses and densities using the Hot Molding Process (HMP). During this process, the CoPET component melts, bonding the remaining fibers. The resulting samples, across all mixtures, have thicknesses ranging from 5 mm to 35 mm, with surface mass varying from approximately 490 to 2700 g/m².

2.2 Method

2.2.1 Experiment approaches

This study aims to define the transport parameters of fibrous materials through experimental data. Various tests were conducted on flat samples, including: (i) identification of transport parameters, (ii) measurement of Normal

Incidence Sound Absorption, (iii) measurement of Diffuse Field Absorption, and (iv) evaluation of Sound Transmission Loss.
From the identified transport parameters, linear or power curve fitting relationships were established. Once the transport parameters were determined, the acoustic performance of the materials were predicted using the "Johnson-Champoux-Allard" (JCA) equivalent fluid model, which requires five key parameters: open porosity ϕ, airflow resistivity σ, tortuosity α_∞ , viscous characteristic length Λ, thermal characteristic length Λ' [1].

2.2.2 Material characterization and acoustic measurements

Diffuse field sound absorption coefficient measurements were conducted on flat samples (1 m × 1.2 m) using a small reverberation room (6.44 m³), known as the Alpha Cabin. Ideally, according to ISO 354 [9], a large reverberation room (>180 m³) and a sample size of 12 m² are required. However, the reduced-size cabin allows for quick measurements with a 1.2 m² sample, which is commonly used in the automotive industry by both suppliers and OEMs.
Transmission Loss measurements were performed using the two-room method, where the flat sample was placed on a 0.9 mm-thick steel plate. Sound intensity and pressure measurements were taken in an anechoic room and a reverberation room, respectively [10].
For each flat sample (1.2 m²), three circular specimens (Ø100 mm) were extracted for airflow resistivity (AFR) measurements [11]. Subsequently, normal incidence sound absorption measurements [12] were carried out using Ø45 mm samples cut from the Ø100 mm specimens, ensuring that measurements were taken from the same locations, see Fig. 1.

Figure 1. Impedance tube samples (Ø45 mm) extracted from AFR samples (Ø100 mm) for different mixtures.

JCA transport parameters were identified for material samples with varying densities and thicknesses but the same raw material composition (i.e., the same mixture). For each given mixture, a minimization-based inversion was performed, simultaneously processing all samples of that mixture to fit the data from AFR and normal incidence sound absorption measurements [13]-[14].

3. RESULTS

3.1 Empirical regression models

Once the JCA parameters were identified for each sample, the datasets were used to develop empirical regression models. For each of the five transport parameters, a unique formulation was derived and validated for all mixtures. These algorithms, referred to as "*Genetic*", enable the calculation of transport parameters for any fibrous material using typical manufacturing inputs, based on linear or power-law relationships: fiber fineness (*dT*, in dTex), the mixing ratio (ω_i, the weight ratio of each fiber type to the total material weight) and the sample bulk density (ρ). The selection of these input parameters was physically justifiable, as the physical properties of fibrous materials depend on their microstructural characteristics [3]. Specifically, fiber diameters and their distribution can be represented by *dT* and ω_i, while the bulk density ρ or the open porosity ϕ represents the volume of solid or air within the material.
When the material density increases, the air volume inside decreases, leading to a linear relationship between porosity and density*:*

$$\phi = 1 - C_1\rho \tag{1}$$

The tortuosity can then be determined using Archie's law:

$$\alpha_\infty = (1/\phi)^\gamma \tag{2}$$

where γ is a constant depending on the material's microstructure [2]. Both constants, C_1 and γ, were determined to fit the identified porosity and tortuosity for the fibrous materials under study.
Previous work [3] has shown that at a fixed density ρ, the airflow resistivity σ is inversely related to fiber diameters. In other words, the thermal permeability k_0, which is linked to the airflow resistivity of porous material via the dynamic viscosity of air η, is inversely related to the total fiber length L_f per cubic meter. This can be formulated using *dT*,

ω_i and ρ. The thermal permeability can finally be computed as:

$$k_0 = \eta/(f_1 \sum_1^n(\omega_i/dT_i)) \quad (3)$$

where f_1 is a 4^{th}-order polynomial function of density ρ and n is the number of fiber populations in the composition.
Fig. 2 shows a strong correlation between the *Genetic* algorithm (Eqn. 3) and the experimental results for static permeability, which is made non-dimensional using the standard fiber mean diameter d_{ref}.

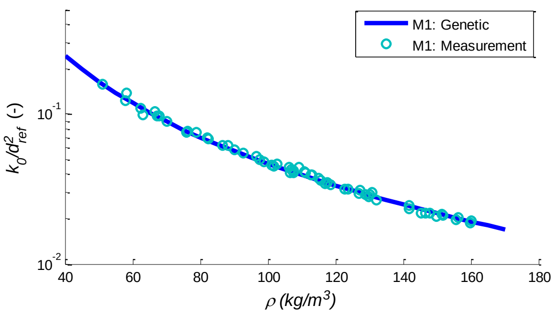

Figure 2. Static Permeability: Correlation between the experimental function (*Genetic* algorithm) and measurements for material mix M1.

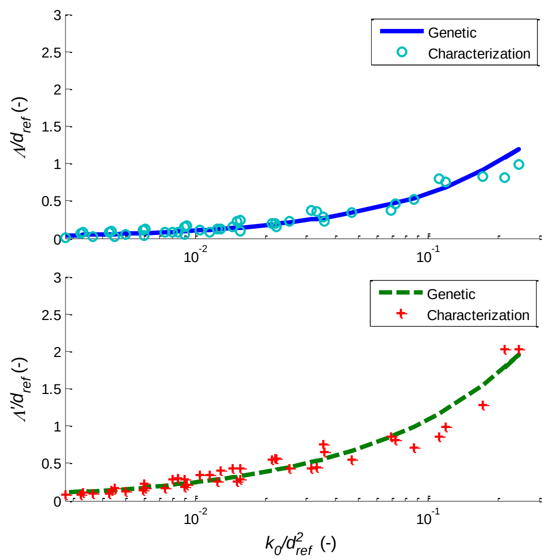

Figure 3. Characteristic Lengths: Correlation between the *Genetic* algorithm and material characterization through global minimization inversion for material mix M1.

As shown in the Eqn. 3, the static permeability k_0 (or airflow resistivity $\sigma = \eta/k_0$), one of the primary factors influencing porous media, contains all the material input parameter information. To put it another way, the two remaining parameters, the characteristic lengths, can be estimated from k_0 using power law functions of the following form:

$$\Lambda = C_2 {k_0}^{C_3} \; ; \qquad \Lambda' = C_4 {k_0}^{C_5} \quad (4)$$

where the coefficients C_i can be easily identified to fit the characterized transport parameters. Using these formulations, good agreement is shown in Fig. 3, with a correlation factor R^2 greater than 0.93 for both characteristic lengths.
For user-friendliness, the *Genetic* functions have been integrated into a transfer matrix simulation tool (internally named PROTEIN), as shown in Fig. 4. Using basic raw material information (e.g., surface mass, thickness, and material composition), the acoustic properties of porous materials can be quickly estimated.

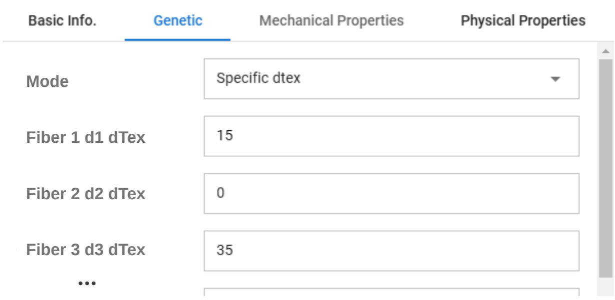

Figure 4. Implementation of a *Genetic* Algorithm model in a Transfer Matrix Simulation (TMM) tool called PROTEIN.

The *Genetic* functions were validated through material performance tests.
Firstly, normal incidence sound absorption, simulated using the Transfer Matrix Method (TMM), showed good correlation with the measurement results, as demonstrated in Fig. 5 for material Mix1. This strong correlation with impedance tube measurements was expected, as such results are commonly used as input for material characterization through inversion approaches. However, this study also presents a strong correlation with diffuse field sound absorption measurements using the Alpha Cabin, as shown in Fig. 6, providing a comprehensive evaluation of absorption performance.

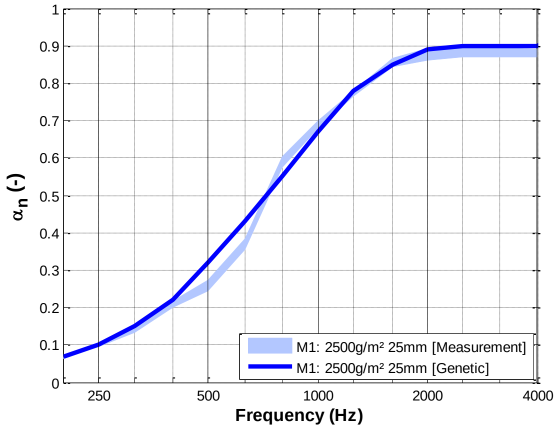

Figure 5. Normal Incidence Sound Absorption: Correlation between the *Genetic* algorithm and impedance tube measurements for material mix M1 at a thickness of 25 mm and density $\rho = 100$ kg/m^3.

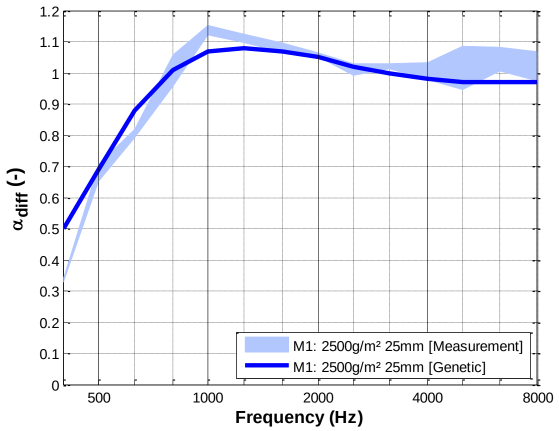

Figure 6. Diffuse Field Sound Absorption: Correlation between the *Genetic* algorithm and Alpha Cabin measurements.

Alpha Cabin measurements are typically problematic for their round robin reliability and the results were not as clear due to the more complex reverberant sound field. However, such a good level of correlation has not previously been reported.

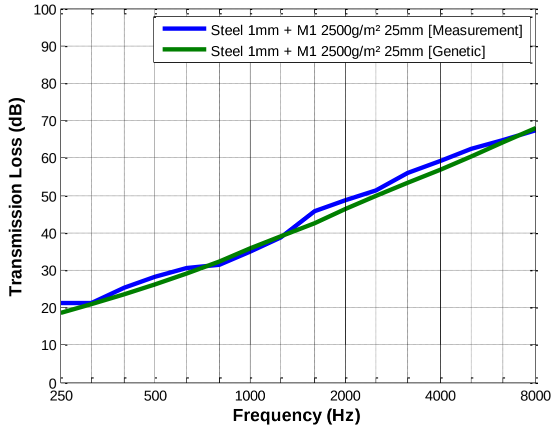

Figure 7. Sound Transmission Loss: Correlation between the *Genetic* algorithm and coupled reverberation/anechoic measurement results.

Additional validation of the *Genetic* algorithms was carried out through Sound Transmission Loss measurements in a simple system where the fibrous flat sample was placed on a steel plate. A good agreement was observed between the simulation and measurement results. Both the acoustic simulations for the Alpha Cabin and Transmission Loss were performed with diffuse field excitation using the Transfer Matrix Method [1].

4. CONCLUSIONS

In this paper, the JCA transport parameters of fibrous materials were computed from raw material information using functions derived from experimental results for various fibrous material compositions and a wide range of bulk densities. These algorithms, referred to as "*Genetic*" were validated, not only through normal incidence sound absorption, but also via diffuse field excitation for both sound absorption and transmission loss. The algorithms were implemented in an internal simulation tool, enabling rapid estimation of acoustic performance based on material typical inputs. This approach has proved useful for several applications, including RFQ responses, manufacturing support and innovation. Future work will involve extending this approach to polyurethane foam materials.

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6. ACKNOWLEDGMENTS

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7. DEFINITIONS / ABBREVIATIONS

OEM – Original Equipment Manufacturer
JCA – "Johnson-Champoux-Allard" (equivalent model)
RFQ – Request for Quotation
TMM – Transfer Matrix Method
AFR – Airflow Resistivity
PET – Polyethylene Terephthalate
CoPET – Copolyester
HMP – Hot Molding Process
dT– Fiber fineness (dTex)
ω_i – Fiber weight ratio
ρ – Material bulk density (kg/m^3)
σ – Airflow resistivity (Ns/m^4)
k_0 – Static thermal permeability (m^2)
ϕ – Open porosity (-)
α_∞ – Tortuosity (-)
Λ – Viscous characteristic length (μm)
Λ' – Thermal characteristic length (μm)
η – dynamic viscosity of air (Ns/m^2)
γ, C_i – "*Genetic*" algorithm constants