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Review paper

MODELS FOR PREDICTING SOUND ABSORPTION OF POROUS MATERIALS

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Branko Radičević

University of Kragujevac, Faculty of Mechanical and Civil Engineering, Kraljevo, Serbia

ORCID iDs: Branko Radičević https://orcid.org/0000-0002-4182-4095

Abstract. *Porous materials are widely used in the field of noise control. The acoustic properties of these materials are best characterized by the sound absorption coefficient, which can be predicted using different mathematical models presented in this paper: empirical, phenomenological, and statistical. Optimization models based on biologically inspired algorithms were used to determine the non-acoustic parameters of the acoustic models. In addition to mathematical models for predicting acoustic parameters of porous materials, the paper also presents models for identifying non-acoustic parameters that are input parameters of empirical and phenomenological models. Air flow resistance is one of the most significant non-acoustic parameters of porous materials, and its values shown in this paper were measured according to the SRPS EN ISO 9053-1:2019 method. In empirical models, resistance to airflow is the only input parameter, while in phenomenological and optimization models it is one of several input parameters that establish a connection between microstructure and acoustic properties of porous materials. Based on the experimental values of the sound absorption coefficient, the non-acoustic parameters of the phenomenological models were determined using biologically inspired optimization algorithms. Statistical models are based on ANOVA analysis and determination of the sound absorption coefficient's dependence on the material layer's thickness and frequency. Predictions of the sound absorption coefficient of open-cell polyurethane foam were determined using the above models and are compared with pipe impedance measurements. In this way, the accuracy of the prediction of mathematical models for determining sound absorption was established. In addition, this research shows that low-density open-cell polyurethane foams have good sound absorption performance over a wide frequency range, and as such can be used for noise protection.*

Key words: *porous materials, acoustic models, sound absorption coefficient*

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Corresponding author: Branko Radičević
University of Kragujevac, Faculty of Mechanical and Civil Engineering, 36000 Kraljevo, Serbia
E-mail: radicevic.b@mfkv.kg.ac.rs

1. INTRODUCTION

Many scientific and professional papers, books, and other literature talk about acoustic materials for sound absorption. The basis of these publications is empirical, stating the acoustic properties of various materials that have been experimentally determined and proposing design methods based on the analysis of empirical data. These methods of designing sound-absorbing materials were the only ones used until recently when materials designed by theoretical analysis of the physical principles of wave mechanics began to appear.

1.1. Porous materials

Porous materials are those materials in which the solid mass is permeated with canals, i.e. pores, interconnected in a continuous network. The sound penetrates deep into the pores of these materials, where, due to high friction, the acoustic energy is converted into heat [1].

Ayub et al. [2] analyzed sound absorption from natural coconut fiber, using the Delany-Bazley model [29]. Navacerrada et al. [3] presented natural fibrous material from tree leaves as an ecological alternative that can be used in construction for noise protection. AL-Rahman et al. [4] studied fibers of natural materials in the direction of sound absorption and environmental pollution protection. It has been proven that the mixture of palm and coconut fibers can replace synthetic fiber materials, such as glass wool, rock wool, and asbestos.

Porous foams can be produced from a large number of different materials. Therefore, it is difficult to give a general approach to studying the acoustic properties of foams and fibrous materials [5]. Polyurethane foams are available in a wide range of densities and thicknesses, so as such they have found wide application in the automotive industry, furniture production, textile, footwear, packaging, and construction [6]. PU foams are increasingly a substitute for mineral and stone wool, which are harmful to human health [7]. Kino et al. [8] presented the acoustic and non-acoustic properties of cross-linked and partially cross-linked polyurethane foams. Pompoli and Bonfiglio [9] conducted an experimental study of polyurethane foams with open cells. Vuković et al. in their work [10] state that changing the composition of the reactants and the conditions of polymer synthesis enables obtaining PU for different purposes.

Research by various authors has shown that materials with the desired acoustic properties can be made from recycled rubber. Pfretzschner and Rodríguez [11], proved that rubber granules can be a good sound absorber, for broadband absorption, which is very suitable for protection against traffic noise. Swift et al. [12] found that these materials can effectively absorb sound if the size of the rubber aggregate granules and the binder content are carefully selected. Han et al. [13] found that recycled rubber granules are an excellent material for combining with concrete to create sound barriers next to high-frequency roads, in places where they pass through residential areas. In the work of Radičević and Ristanović [14], the results of research into the acoustic properties of materials based on recycled rubber are presented.

Composite materials are increasingly used for sound insulation. Composites that can be characterized as "green" are especially important. Zainulabidin et al. [15] studied the acoustic properties of a mixture of rubber sponges and glass wool fibers. Theophilus et al. [16] examined and analyzed the absorption properties of a mixture of sawdust, gypsum, mud, and sand, mixed in different amounts. Mahzan et al. [17] studied a mixture of natural rice husk fibers with polyurethane foam that serves as a binder.

1.2. Some methods for determining acoustic properties

1.2.1. Determination of resistance to airflow

Air flow resistance is a basic non-acoustic parameter that affects the sound absorption of porous materials [18]. Certain authors [9,19,20] pointed to the problem of excessive errors when determining the resistance to airflow, which is primarily due to the inhomogeneity of the samples. Dragonetti et al. [18] developed a method for measuring resistance to airflow, based on alternating airflow, which does not require calibration, so it can be implemented in most acoustic laboratories. Ingard and Dear [21] proposed measuring the resistance to airflow in a pipe with a sound source. In the scientific literature, there are few works devoted to predicting the resistance to airflow of porous materials [22]. Bies and Hansen [23] presented a model that allows calculating the resistance to airflow starting from the density and diameter of the fiber of the porous material. Kino and Ueno [24] developed a new relationship between the longitudinal resistance to flow and the density of melamine foam, using the equivalent fiber diameter. Garai and Pompoli [22] presented a simple model that allows the calculation of flow resistance depending on the density of the polyester fiber material. Vigo Tarnow [25] presented a new way of calculating the longitudinal resistance to airflow for a set of randomly placed parallel cylinders.

1.2.2. Measurement of the coefficient of sound absorption in an impedance tube

The measurement of the normal acoustic impedance of a porous material is standardized by the EN ISO 10534-2 method [26]. Janiv [27] proposed a method for deriving the propagation constant and characteristic impedance. Utsuno et al. [28] proposed a new method with two cavities. Using propagation constant and characteristic impedance data, the normal incidence absorption coefficient can be predicted for different sample thicknesses. Predictions of absorption coefficients at normal incidence with different thicknesses of air layers located in front of the rigid substrate are also possible.

1.3. Models for predicting the acoustic properties of porous materials

In the scientific literature, there are many works dedicated to predicting the characteristic acoustic impedance and expansion constant of porous materials. By introducing the hypothesis of plane progressive wave propagation, the sound absorption coefficient can be easily determined. Those models can be classified according to Garai and Pompoli [22], as empirical, phenomenological, or microstructural.

1.3.1. Empirical models

Among the empirical models, the most famous is the one defined by Delany and Bazley [29], in which they presented simple expressions for complex functions of acoustic impedance and wave number, obtained by regression analysis of a large number of experimental samples. In the mentioned model, only one input parameter appears, the airflow resistance, which is relatively easy to measure. Due to its simplicity, this model is probably the most well-known, considering its citations. Delany and Bazley defined diagrams for evaluating the airflow resistance of fibrous materials as a function of their density. Dunn and Davern [30] kept the same form of the model, but for polyurethane foams they determined new values of regression constants in characteristic impedance and propagation constant, using experimental samples of polyurethane foams with low values of resistance to airflow. Using essentially the same methodology, the works of Voronina [31,32] show the characteristic impedance and expansion constants as a function of fiber diameter and porosity. Gardner et al. [33] used a neural network to implement an empirical model, using airflow resistance as the only input parameter in the model.

1.3.2. Theoretical models

The sound absorption of porous materials can be studied using "equivalent fluids", characterized by two macroscopic dynamic properties, bulk density and bulk modulus of elasticity, which take into account viscous and thermal effects between the porous structure and the interstitial fluid. Hammet [34] took thermal and viscous dissipation into account in his extended phenomenological model. Significant progress in the development of theoretical models was made by Biot [35], who developed a general theory of the propagation of elastic waves in a fluid saturated with a porous rigid, and elastic frame. Using Biot's results, Lambert [36] developed an analytical model for highly porous polyurethane foams, whose verification he confirmed by measuring some structural parameters.

An approach of a more general nature, known as the microstructural approach, consists of performing wave propagation within individual pores, and thus generalizing the results at the macroscopic level. Zwikker and Kosten [37] applied this procedure for unconnected circular pipes. Allard et al. [38] formed a model using the dynamic density function given by Biot [35], the expression for the dynamic bulk modulus of elasticity presented in the work of Zwikker and Kosten [37], and the frequency-independent shape factor. Champoux and Stinson [39] proposed another model with 5 parameters, including two different shape factors that take into account viscous and thermal effects. The model has been validated on porous materials that have exactly the specified geometry of the structure.

1.3.3. Statistical models

To determine the sound absorption coefficient using statistical models [40], it is necessary to carry out a regression analysis procedure and select an adequate model after choosing an experimental plan and conducting experimental measurements.

1.3.4. Optimization models

Many optimization techniques have been adopted to perform inverse acoustic characterization in recent years.

Atalla and Panneton [41] found the non-acoustic parameters for the porous material of a rigid frame using the Johnson–Champoux–Allard model [42] using the genetic algorithm optimization method. They also extended this to a multi-layer material configuration. Based on the differential evolution algorithm, Atalla and Panneton [43] solved the inverse problem of characterizing three input parameters in the JCA model. Pelegrins [44] solved the error minimization problem using the simplex optimization method. Cobo et al. [45] used a simulated annealing algorithm for determining non-acoustic parameters of granular acoustic absorption materials. Bonfiglio and Pompoli [46] gave a comparative account of the different methods used to determine the physical parameters of porous materials. The research results from the literature [46] show that the analytical method and the iterative method are difficult to deal with nonlinear constraints and that the optimization solution time of the iterative method is relatively long. The local search ability of the genetic algorithm is relatively weak, and the encoding and decoding process is quite complex.

The measuring devices listed in [47] are not a common part of acoustic laboratories, so the use of the inverse acoustic characterization method helps a lot in determining these parameters. In inverse characterization methods, the main focus is on reducing the error between experimental data and theoretical data that are the result of the prediction of different analytical models.

Multi-criteria optimization for the selection of absorption materials is very rarely represented in the scientific literature. The basic problem consists of the impossibility of reliably generating a large number of alternatives that meet specific acoustic requirements for specific cases of noise protection.

The paper [48] shows the application of the Taguchi method in the optimization of sound transmission losses through sandwich plaster constructions and those consisting of concrete masonry blocks and plasterboards. Using the Taguchi method, the relative influence of various parameters affecting sound transmission losses was investigated. Analytical predictions of the "Insul" software were used in the paper for different sandwich materials. The authors point out that the application of the Taguchi method for the optimization of sound transmission losses has rarely been published in scientific papers. Statistical analysis of variance (ANOVA) was conducted to determine significant parameters. The paper presents two case studies related to the optimization of sound insulation using the Taguchi method for multi-layered building elements, using the analytical results of the "Insul" software.

2. EXAMPLES OF ACOUSTIC MODELS FROM THE LITERATURE

2.1. Delany-Bazley model

In 1970, Delany and Bazley [29] presented a model for determining the characteristic impedance, Z_0, and the expansion coefficient γ, depending on the longitudinal resistance to airflow of the porous material.

$$Z_0 = R + jX \tag{1}$$

$$\gamma = \alpha + j\beta \tag{2}$$

After a large number of measurements in the impedance tube for materials with different resistance to airflow and a specific frequency range, Delany and Bazley [29] established the laws of change in impedance and coefficient of propagation as complex quantities as a function of the ratio of frequency and longitudinal resistance to airflow.

These regularities can be written as a function of a dimensionless term, which is obtained when the ratio of frequency and longitudinal resistance to airflow is multiplied by the density of the fluid, $\rho_0 f/\sigma$, which Delany and Bazley [29] call the normalized dimensionless parameter. Laws established by Delany and Bazley [29], taking into account the international system of units, can be expressed in the form:

$$Z_c = \rho_0 c\left[1+0.0571\left(\frac{\rho_0 f}{\sigma}\right)^{-0.574} - j0.087\left(\frac{\rho_0 f}{\sigma}\right)^{-0.732}\right] \tag{3}$$

$$k_c = \frac{\omega}{c}\left[1+0.0978\left(\frac{\rho_0 f}{\sigma}\right)^{-0.7} - j0.189\left(\frac{\rho_0 f}{\sigma}\right)^{-0.595}\right] \tag{4}$$

The model assumes that the absorbent material is fibrous and that the fibers are uniformly distributed. Delany and Bazley [29] defined the domain of functions in their empirical model:

$$10 \le f\,/\,\sigma \le 1000 \tag{5}$$

where the frequency f is expressed in Hz and the longitudinal resistance to airflow, σ, in kg/m^{3}s.

The validity range of the model can be expressed through a dimensionless parameter in the form: $0.01 \le \rho_0 f/\sigma \le 1$.

It should be noted that all fibrous materials considered in this model have porosity close to unity.

2.2. Johnson – Champoux – Allard (JCA) model

As a semi-empirical model, the JCA model [42] is the most commonly used sound absorption model. It contains five physical parameters, namely porosity ϕ, airflow resistance σ, tortuosity α, viscous characteristic length Λ, and thermal characteristic length Λ'. Porosity is the percentage of pore volume occupied by a saturated medium (usually air) compared to the total volume of the material in its natural state. Airflow resistance has an important effect on the sound absorption performance of porous materials. It is usually defined as the resistance of air flowing through a porous material of a certain thickness. The tortuosity of porous materials is the deviation between the actual path and the true path of sound waves in the materials, which represents the complexity of the pores of the material. Both porosity and tortuosity are dimensionless quantities. The viscous characteristic length represents the size of the viscous force, and the thermal characteristic length describes the degree of heat exchange between the saturated medium in the pore and the solid frame at high frequencies [49].

According to the JCA model, the effective density $\rho e(\omega)$ and bulk modulus K(ω) of porous materials can be calculated using the following expressions:

$$\rho_e(\omega) = \alpha_\infty \rho_0\left[1 - j\frac{\sigma\phi}{\alpha_\infty \rho_0 \omega}\sqrt{1 + j\frac{4\alpha_\infty^2 \eta \rho_0 \omega}{\sigma^2 \Lambda^2 \phi^2}}\right] \tag{6}$$

$$K_e(\omega) = \gamma P_0\left[\gamma - \frac{\gamma - 1}{1 - j\dfrac{8\eta}{\rho_0 \omega N_{pr} \Lambda^{'2}}\left(1 + \sqrt{1 + j\dfrac{\rho_0 \omega N_{pr} \Lambda^{'2}}{16\eta}}\right)^{\frac{1}{2}}}\right]^{-1} \tag{7}$$

where ω is the angular frequency of the incident wave, j is an imaginary unit, ρ_0 is the air density, N_{pr} is the Prandtl number of the air, η is the dynamic viscosity of the air, γ is the specific heat ratio related to the state of the air, and P_0 is the ambient atmospheric pressure. It should be noted that Λ and Λ' are related to some other physical parameters of the material and can be written as:

$$\begin{aligned} \Lambda &= \frac{1}{c}\left(\frac{8\alpha_\infty\eta}{\sigma\phi}\right)^{\frac{1}{2}} \\ \Lambda' &= \frac{1}{c'}\left(\frac{8\alpha_\infty\eta}{\sigma\phi}\right)^{\frac{1}{2}} \end{aligned} \tag{8}$$

where c and c' are the shape factor and the scale factor of the pore cross-section, respectively.

The characteristic impedance $Z_c(\omega)$ and the complex expansion constant $k(\omega)$ of porous materials can be deduced from Eqs. (3) and (4), and can be expressed as Eqs. (9) and (10).

$$Z_c(\omega) = \sqrt{K_e(\omega)\rho_e(\omega)} \tag{9}$$

$$k_e(\omega) = \omega\sqrt{\frac{\rho_e(\omega)}{K_e(\omega)}} \tag{10}$$

Considering that the porous material of thickness d is covered by a rigid boundary, the sound absorption coefficient (SAC) α of the porous material can be denoted by the following equations:

$$Z_s(\omega) = -j\frac{Z_c(\omega)}{\phi}\cot(k_e(\omega)d) \tag{11}$$

$$R = \frac{Z_s(\omega) - Z_o}{Z_s(\omega) + Z_o} \tag{12}$$

$$\alpha = 1 - R^2 \tag{13}$$

where $Z_s(\omega)$ is the surface characteristic impedance, Z_0 is the air characteristic impedance, and is equal to $\rho_0 c_0$ where c_0 is the sound speed and R is the sound reflection coefficient.

To determine the impedance of the finite thickness of the material Z_l, in front of the rigid wall, knowing the values of the estimated surface impedance using different models, the following expression is used:

$$Z_l = Z_c\coth(jk_c d) \tag{14}$$

where d is the sample thickness.

Estimates of impedance and absorption coefficient calculated according to different empirical models are compared with the values of these quantities measured in the impedance tube.

2.3. Methodology of forming stochastic models

The software package Design Expert v.9.0.6.2 was used to create and analyze stochastic models. The choice of the regression model depends, first of all, on the available number of experimental points. However, even when there is a sufficient number of experimental points, it does not mean that the model of the highest degree will be the best. Models are formed in the form of polynomials of the nth degree. For experiments with mixtures, polynomials up to the fourth degree are used, and for other experiments polynomials up to the sixth degree.

To select a stochastic model, a summary statistical analysis is used, which compares possible models based on: standard deviation (Standard Deviation), coefficient of determination (R-squared), adjusted coefficient of determination (Adjusted R-squared), assumed coefficient of determination (Predicted R-squared) and PRESS statistics (Prediction Sum of Squares Statistic).

The sound absorption coefficient can be expressed by a polynomial function, as given in the expression [41] for open and partially open-cell polyurethane foams:

$$\begin{gathered} Ln(\alpha) = -2.15980 - 51.64481 * d - 3.46202E - 003 * f + \\ +0.28361 * d * f + 1164.37919 * d \wedge 2 + 3.54443E - 006 * f \wedge 2 - \\ -2.87696 * d \wedge 2 * f - 1.56509E - 004 * d * f \wedge 2 - 6589.93271 * d \wedge 3 - \\ -1.19549E - 009 * f \wedge 3 + 3.58649E - 004 * d \wedge 2 * f \wedge 2 + 11.80043 * \\ * d \wedge 3 * f + 3.97690E - 008 * d * f \wedge 3 \end{gathered} \tag{15}$$

where *d* is the thickness of the material in m, and *f* is the frequency in Hz.

2.4. Non-acoustic parameter identification models

In the JCA model, there are five non-acoustic parameters to be identified: porosity, airflow resistance, tortuosity, viscous characteristic length, and thermal characteristic length. Often this problem boils down to finding four unknown parameters, as porosity can be determined with high accuracy from measured density. In this way, the dimension of the vector $x = [\sigma, \alpha_\infty, c, c^{'}]$ is reduced by one.

The viscous characteristic length Λ and the thermal characteristic length Λ' are functions of the shape factor *c* and the scale factor *c´* of the pore cross-section, respectively. The range of values of characteristic length is usually from 1 to 3000, while the value of shape factor *c* or scale factor *c´* generally ranges from 0.3 to 3.3. Shape factor *c* and scale factor *c´* were chosen as design variables instead of viscous characteristic length and thermal characteristic length because narrowing the solution space helps to arrive at a reasonable solution [49].

Non-acoustic parameter identification is essentially a constrained multidimensional parameter optimization problem. According to the principle of the least square method, the objective function and the constraints can be given by Eq. (16):

$$\begin{gathered} \min f_{obj}(f_i, \mathbf{x}) = \sum_{i=1}^{T} \left[\alpha_{EXP}(f_i) - \alpha_{JCA}(f_i, \mathbf{x}) \right]^2 \\ s.\,t. \begin{cases} 1000 \le \sigma \le 20000 \\ 1 \le \alpha_\infty \le 4 \\ 0.3 \le (c, c^{'}) \le 3.3 \\ c \ge c^{'} \end{cases} \end{gathered} \tag{16}$$

where T is the number of sampling frequency points in the test frequency range, f_i is the ith frequency point sampled in the experiment, α_{EXP} denotes the sound absorption coefficient measured at the frequency f_i, and α_{JCA} denotes the sound absorption coefficient predicted by the JCA model at the same frequency.

3. CONCLUSIONS

Empirical models are characterized by their simplicity since they depend on only one input parameter, the resistance to airflow, which can be measured relatively easily. Precisely because of this, the resistance to airflow must be determined by applying valid methods, which enable the calculation of the sound absorption coefficient in a wide frequency spectrum. The disadvantage of these models in terms of the breadth of application is that they were developed for a specific material or a specific group of similar materials. Precisely because of this, empirical models sometimes do not give good predictions in certain frequency ranges, and most often these are low frequencies. Given that these models are most often obtained by applying regression analysis and the method of least squares, often for a certain type of material the regression constants cannot be more accurately determined by applying optimization techniques.

Theoretical models or phenomenological as they are also called, which are used to determine sound absorption, are much more complex compared to empirical models. Theoretical models penetrate the physicality of the process, most often through the determination of bulk density and bulk modulus of elasticity, which take into account viscous and thermal effects between the porous structure and the interstitial fluid. The advantage of such models is that optimal process parameters can be indirectly determined in the phase of making porous materials, to achieve the desired acoustic properties. The shortcoming of theoretical models is that the most frequently used five parameters of different models cannot be determined within the model, but additional measurements are required using expensive and specialized measuring equipment.

Statistical models that are primarily based on ANOVA analysis can be very useful when solving the problem of applying absorption materials in noise protection systems. They can be useful when it is necessary to determine the optimal thickness of absorption material for a certain frequency range, or for a given thickness to determine the type of material that will achieve a given level of sound protection. Considering that they are polynomial functions of a higher order, these models give a very precise match of the sound absorption coefficient with the experimental values. The disadvantage of these models is that they are not reliable for frequency ranges for which there are no experimental sound absorption results.

Models based on the application of genetically inspired algorithms for determining the sound absorption of porous materials are more recent. By solving the optimization problem of multidimensional parameters, non-acoustic identification of parameters is performed, which is very important considering the problems during their determination. Solving optimization problems requires an enviable programming experience, which can be considered a shortcoming of these models. Applying optimization algorithms to models that have one input parameter often does not give satisfactory results. By applying optimization techniques, phenomenological models for determining the sound absorption of porous materials are becoming more widely represented.

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