Methodology to assess the relationship between acoustic absorption coefficient, thickness and frequency response

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Abstract: Sound absorption coefficient is a commonly used parameter to characterize the acoustic properties of sound absorbing materials that plays an important role in noise attenuation. Commonly, the laboratory experiments stand as basics to determine which thicknesses is more appropriate to be used and on what frequency is obtained the optimum acoustic absorption coefficient. This method is time and money consuming. A more inexpensive method is to use noise simulation, but some adaptations most be performed in order to have a very good accuracy. This paper provides a simple reasonable methodology to assess the relationship between acoustic absorption coefficient, thickness and frequency response. For this study a specific material has been chosen in order to exemplify the methodology and was experimentally evaluated and compared with the simulated results to validate the simulation model. The method used to estimate the sound absorption coefficient is based on transfer function method in accordance with standard SR EN ISO 10354-2. Using simulations, different thicknesses were considered and the acoustic absorption coefficient in relation with the frequency response was assessed, facilitating an easier way to select the proper material thicknesses to design a specific acoustic solution.

Key-Words: material noise reduction, sound absorption coefficient, acoustic FEM, Kundt tube, transfer function, methodology, optimization

1 NOMENCLATURE

C	damping matrix
$F(\omega)$	load matrix
K	stiffness matrix
L	mesh element length
M	mass matrix
R	real part of acoustic impedance
$R(\omega)$	reflection factor
V	velocity
X	imaginary part of acoustic impedance
Z	acoustic impedance
c	speed of sound
d	inner diameter of the tube
f	frequency
h	material thickness
k	complex wave number
n	structure factor
r	reflection coefficient
s	distance between microphone positions
α	sound absorption coefficient
λ	wave length
ρ	effective density
σ	static air flow resistivity
ω	angular frequency
E_i	incident sound energy
E_r	absorbed sound energy
H_I	transfer function for incident wave

H_R	transfer function for reflection wave
H_{12}	transfer function
Z_c	characteristic impedance
c_0	speed of sound in air
f_u	upper frequency limit
f_l	lower frequency limit
x_1	distance from microphone 1 to sample
x_2	distance from microphone 2 to sample
p_1	acoustic pressure at microphone 1
p_1'	air pressure after sample
p_2	acoustic pressure at microphone 2
p_1'	air pressure before sample
p_i	incident acoustic pressure
ρ_0	air density

2 Introduction

Numerous works have been devoted to the study of porous absorbing materials, which are applied in various fields of noise control. Examples can be found in fields of building and room acoustics, industrial and environmental noise control or transportation industry. The trend in research is directed towards the development of smaller, lighter and cheaper structures which are acoustically efficient as the existing ones. The acoustic properties and cost efficiency of materials must be taken into account together with the experimental costs.

Each noise solution must be designed taking into account its specific and first of all, noise measurements must be performed, such that the frequency spectrum of the noise source is known. Acknowledging the frequency distribution, one can act directly on the noise source dominant frequency, by choosing the optimum material considering its acoustic properties and the right thicknesses. Several studies highlighted the FEM advantages, which consist in the possibility of assessing multiple case studies in shorter time [1] [2] [3].

3 Theoretical backgrounds

A method to determine the acoustic parameters of a material is the standing wave ratio (SWR), where a traversing microphone is used to determine the location and magnitude of successive maxima and minima of the standing-wave pattern in a tube. Then from these reflection coefficient is deduced and the acoustic absorption coefficient is determined.

Another method is the transfer function, which uses generation of plane waves in the tube by a sound source emitting a white noise, and the sound pressure level is measured in two locations close to the sample.

The results from both methods are closed, but the two microphones transfer function technique offers numerous advantages in comparison with the standing waves method, including less time in laboratory experiments, the errors of the human factor are reduced and the results are accurate [4].

This paper is addressing to a large public and in order to become a comprehensive one, the aim of this chapter is to review the followings acoustic concepts: transfer function method using two microphones, sound absorption coefficient and acoustic impedance.

Sound absorption coefficient describes the efficiency of the material or the surface to absorb the sound. The energy which is absorbed is usually the result of conversion into another form of mechanical energy which is generally heat and this may be achieved in several different ways. The amount of sound energy which is absorbed is described as the ratio of sound energy absorbed to the sound energy incident, and is termed the ‘sound absorption coefficient’ [5].

According to standard SR EN ISO 10534:2002 [6], we may write:

$$\alpha = \frac{E_i - E_r}{E_i} \tag{1}$$

where α = sound absorption coefficient.

The transfer function between the two microphones used for determining the acoustic absorption is given by:

$$H_{12} = \frac{P_2(\omega)}{P_1(\omega)} = \frac{S_{12}(\omega)}{S_{11}(\omega)} \tag{2}$$

where: $H_{12}(\omega)$ is the transfer function from microphone position one to two,

$P(\omega)$ is the Fourier transform of the acoustic pressure;
$S_{12}(\omega)$ is the cross spectrum and is the product $P_2(\omega)P_1(\omega)^*$, determined from the complex sound pressures $P_1(\omega)$ and $P_2(\omega)$ at two microphone positions;
* represents the complex conjugate;
$S_{11}(\omega)$ is the auto spectrum and is the product $P_1(\omega)P_1(\omega)^*$, determined from the complex sound pressure $P_1(\omega)$ at microphone position one.

In order to correct the amplitude and phase mismatches between microphones a calibration factor $H_c(\omega)$ is used. The calibration procedure uses a special calibration specimen and the correction is valid for all successive measurements. This procedure is performed only once and after calibration the microphones are remaining in place.

First, an absorptive specimen is placed in the tube to prevent strong acoustic reflections and the next step is to measure the two transfer functions $H_{12}^{I}(\omega)$ and $H_{12}^{II}(\omega)$.

Notice that:

$$H_{12}^{I}(\omega) \text{ is } P_2/P_1 = P_B/P_A \tag{3}$$

$$H_{12}^{II}(\omega) \text{ is } P_2/P_1 = P_A/P_B \tag{4}$$

As can be observed, this procedure consist in the interchanging the positions of the microphones. After the both transfer function have been measured the calibration factor is determined as:

$$H_c(\omega) = \sqrt{H_{12}^{I}(\omega)H_{21}^{II}(\omega)} = |H_c|e^{j\phi} \tag{5}$$

Then the corrected transfer function $H_{12}(\omega)$ is determined from the uncorrected transfer function $\hat{H}_{12}(\omega)$:

$$H_{12}(\omega) = |H_{12}|e^{j\varphi} = \frac{\hat{H}_{12}(\omega)}{H_c(\omega)} \tag{6}$$

from which the reflection coefficient is extracted as follows:

$$R(\omega) = |R|e^{j\varphi_R} = \\ = \frac{H_{12}(\omega) - H_i}{H_r - H_{12}(\omega)}e^{2jk_0x_1} = \frac{e^{-jk_0s} - H_{12}}{H_{12} - e^{jk_0s}}e^{2jk_0x_1} \tag{7}$$

where: $H_I = e^{-jks}$ is the transfer function of the incident wave alone;

$H_R = e^{jks}$ is the transfer function of the reflected wave alone;

$s = x_1 - x_2$ being the distance between the measurement points;
x_1 is the distance between the sample and the further microphone location.

The normal incidence sound absorption coefficient is given by the following equation:

$$\alpha(\omega) = 1 - |R|^2 \tag{8}$$

The acoustic surface impedance ratio is the surface impedance normalized respect to the characteristic impedance of the air:

$$\frac{Z_s(\omega)}{\rho c_0} = \frac{Z_s(\omega)}{Z_0} = \frac{1+R}{1-R} \tag{9}$$

The absorption coefficient is a parameter that varies between the value of 0 (zero absorption, total reflection) and 1 (total absorption). Thicker materials absorb more sound energy (particularly important at low frequency) [7].

4 Methodology descriptions

Hereafter the proposed methodology is schematically presented. It consists of a set of steps that makes the research replicable and assures the validity, figure 1. The basic idea behind this methodology is to reduce the time spent in obtaining the optimum solution to reduce a specific noise source, in terms of frequency response, acoustic absorption coefficient and material thickness. In order to decrease the time for experiments and post-processing the data, to reduce the costs for buying different material samples with several thicknesses the methodology proposes to use FEM simulation. Another advantage in using simulation is that after validating the model one can obtain a big set of data without being necessary additional efforts. The first step is measuring one single material sample, followed by simulations of the same sample, the two results being compared in Step 3. The crucial point in the methodology is given by the validation sequence. If good correlation between measurements and simulations is not obtained, the whole methodology fails, so it becomes imperative to calibrate the simulation. Having a validated simulation model, different thicknesses can be analysed and the interdependencies determined. A complete description of each step is offered in the following subsections.

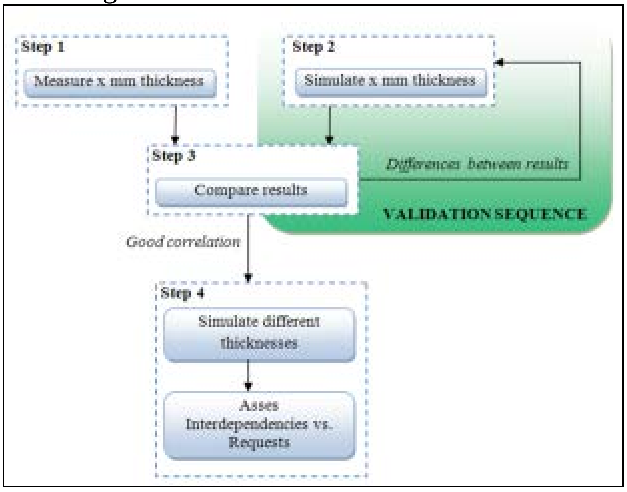

Fig. 1 – Methodology schematic view

4.1 Step 1 - Experimental procedure

4.1.1 Measurement Set-up

The acoustic absorption coefficient was obtained using Kundt Tube system (Fig. 2a), comprising of: two impedance tube Φ 28 and Φ 100, two GRAS 40BP microphones together with G-26AC preamplifiers. The impedance tubes and microphones are connected at SYMPHONIE acquisition system, data being collected and analyzed with dBAlfa software. To measure in 160Hz to 6.3 kHz frequency range, two tubes of different diameters: 100 mm and 28 mm were considered. One can obtain best possible precision if more than 3 microphones positions are used. For the purpose of the present study, the 2 microphone method was used being standardized and proved to offer good results, SR EN ISO 10534-2. The measurement method is based on transfer-function method that consists in measuring the acoustic pressure in two fixed positions (Fig. 2b) and evaluates the complex function of acoustic transfer and the acoustic absorption at normal incidence.

a)

b)

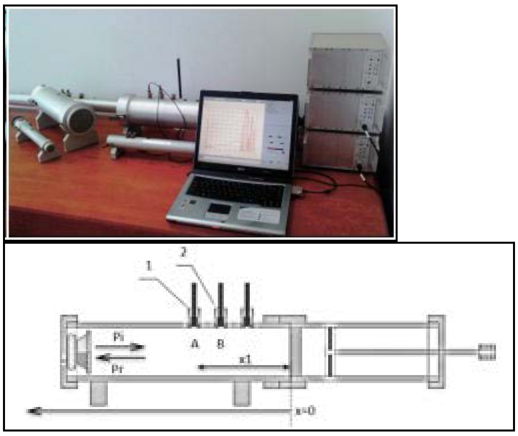

Fig. 2 - Kundt Tube system: a) System components; b) Schematic representation

4.1.2 Laboratory Experiments

Tests were performed in order to evaluate the sound absorption coefficient. The tests were carried out using recycled glass wool of 15mm thicknesses.

Fig. 3 - Tested glass wool samples 15 mm

The absorption coefficient is a function of frequency and was determined on 1/3 octave bands. The graphs in Fig. 4 represent the measured absorption coefficient.

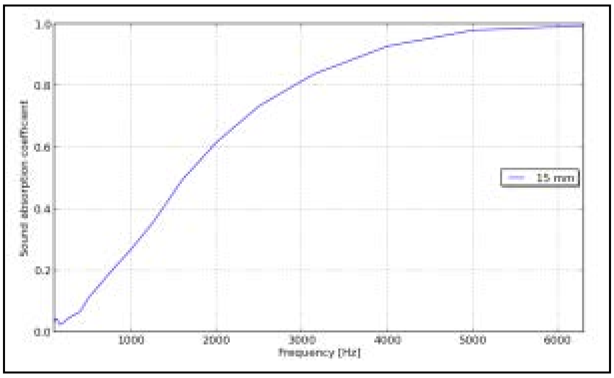

Fig. 4 - Acoustic absorption of glass wool sample

4.2 Step 2 - numerical simulation

In order to carry out cost and time efficient studies numerical simulation becomes an important tool which doesn't requires building real models or performing testing procedures for material characterization. By means of a computer program based on the finite element method, the numerical simulation technique has been applied for the comparative evaluation of the results with experimental data, later elaborated within this paper.

4.2.1 Finite-Element Method

Finite Element Method (FEM) represents a numerical approximation of the solution for a differential equation based on the transformation of the continuous medium into a discrete calculation model, playing an important role in the study of acoustic, vibro-acoustic and aero-acoustic phenomena's. In FEM the infinite numbers of values are reduced to a finite number of unknowns, degree of freedom, created arbitrary by the analyst. The degrees of freedom are independent quantities (quantitative) used to define the configuration of a system.

ACTRAN MSC software uses direct frequency response for the computation of the vibro-acoustic or aero acoustic response of a system (including radiation) in the frequency domain in physical coordinates.

The following system of equations is set-up and solved for various pulsations $\omega = 2\pi f$:

$$(\boldsymbol{K} + j\,\omega\,\boldsymbol{C} - \omega\,2\boldsymbol{M})\boldsymbol{x}(\omega) = \boldsymbol{F}(\omega) \qquad (10)$$

yielding values of the unknown vector $\boldsymbol{x}(\omega)$ for every pulsation ω.

4.2.2 Porous Material Simulation

Porous materials are commonly used as sound absorbing materials with many applications in the field of noise attenuation. For the evaluation of these materials Biot's phenomenological model becomes useful, predicting the behaviour of sound propagation in materials with a flexible skeleton. ACTRAN software also uses the Biot formulation in order to model porous materials. As these porous materials have elastic skeletons which can transmit sound waves and the displacement of the solid part being significant, specific Biot properties have to be provided for the numerical simulation [8].Those properties are divided in:

- Fluid properties (fluid density, fluid bulk modulus, dynamic viscosity, fluid thermal conductivity, specific heat at constant pressure and specific heat at constant volume);
- Fluid-skeleton properties (solid porosity, flow resistivity, Biot factor and tortuosity);
- Micro model parameters (viscous length, thermal length, static thermal permeability, static viscous tortuosity and static thermal tortuosity);
- Elastic parameters (solid density, skeleton Young modulus and skeleton Poisson ratio) [9].

There are available also other simplified models that requires less data about the porous material properties. The rigid porous formulation is used when the material skeleton is assumed rigid, so that the flexibility can be neglected. On the other hand the lumped porous formulation is used when the material skeleton can be assumed extremely soft and its stiffness can be neglected. Semi-empirical numerical models like Delany-Bazley and Miki Porous represent an important tool for modelling porous materials due to the fact that only one parameter (air flow resistivity) is needed to describe the acoustic behaviour [10].

Performing a large number of experimental measurements on fibrous materials with porosities close to 1, Delany and Bazley have defined the following empirical expressions for the complex wave number, k, and characteristic impedance, Z_c, for such materials:

$$Z_c = \rho_0 c_0 \left[1 + 9.08 \left(10^3 \frac{f}{\sigma} \right)^{-0.75} - j11.9 \left(\right. \right. \qquad (11)$$

$$k = \frac{\omega}{c_0} \left[1 + 10.8 \left(10^3 \frac{f}{\sigma} \right)^{-0.70} - j10.3 \left(10^3 \right. \right. \qquad (12)$$

Where: ρ_0 is the density of air;

c_0 is the sound speed in air;

$\omega = 2\pi f$ is the angular frequency;

σ is the static air flow resistivity in the wave direction of propagation.

The boundaries for the expressions validity presented above are:

$$0.01 < \frac{f}{\sigma} < 1.00 \tag{13}$$

If the material is placed in a pipe and a differential pressure induces steady flow of air, the flow resistivity σ is given by [11]:

$$\sigma = \frac{p_2{}' - p_1{}'}{Vh} \tag{14}$$

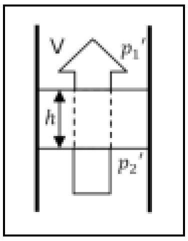

Fig. 5 - Segment of porous material place in a pipe

4.2.3 Simulation

An ACTRAN 2D finite element model is created for each impedance tube (100mm, 28mm) in order to reduce meshing and computing time. The mesh is created using BOXPRO, an ACTRAN meshing tool, which create quickly box-like geometry mesh for simple problem. In this section the elements were not distorted, therefore only the effect of refinement was present. Furthermore the mesh was uniform throughout the domains of the mesh. The inside air volume of the impedance tubes, the porous material medium and the acoustic excitation are modelled. The components of the model are defined and boundary conditions are applied for acoustic excitation component.

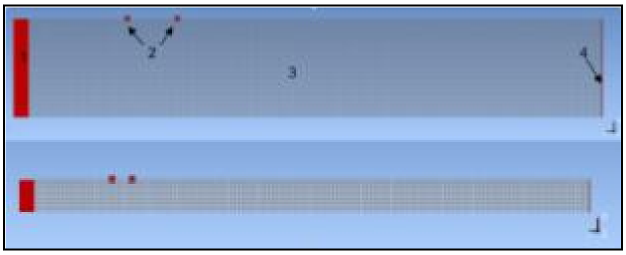
Fig. 6 - Mesh components
(1-Porous material; 2-Microphones; 3-Air;
4-Acoustic excitation component)

The frequency range of computation is specified through the properties of the analysis, while the maximum frequency is driven by the largest element length (e.g. smallest wave). For the large tube the analysis is performed from 160Hz up to 1600Hz with a step of 10 Hz and for the small tube is set to 1600Hz up to 6300Hz.

For linear elements, a rule of thumb is to use 4 quadratic elements per wavelength to capture the acoustic fluctuation.

$$f_{max} = \frac{c}{\lambda_{min}} \tag{15}$$

$$L_{max} = \frac{\lambda_{min}}{4} \tag{16}$$

For large tube the largest element length in the mesh is 5 cm:

$$f_{max} = \frac{340}{4 * 0.05} = 1700Hz \tag{17}$$

For small tube the largest element length in the mesh is 1.2 cm:

$$f_{max} = \frac{340}{4 * 0.012} \cong 7000Hz \tag{18}$$

The 2D mesh has an acoustic part, defined as air and surrounded by rigid wall boundary condition (perfect reflection), along with a Delany-Bazley Porous part composed by a poroelastic material.

The properties requested as input by the Delany-Bazley model were provided from the material specifications of the glass wool that was also experimentally measured on the Kundt Tubes. The two microphones were located in the same position as on the Kundt Tubes in order to apply the transfer function principle as on experimental set-up, assuring a correct data for comparative analyse. A 1m/s velocity boundary condition is applied on the other end of the tube and a direct frequency response numerical analyse is performed for the 160Hz– 6.3 kHz frequency domain. To solve the system of equations (10) for direct frequency response in Actran was used Mumps Solver.

In Actran the absorption coefficient is determine according the below equations:

$$R(\omega) = \frac{H_{12} - e^{-jks}}{e^{jks} - H_{12}} * e^{2jkx_1} \tag{19}$$

$$\alpha = 1 - |R(\omega)|\hat{}2 \tag{20}$$

Where: R(ω) is reflection factor;

$s = x_1 - x_2$;

x_1 is the distance from microphone 1 to sample;

x_2 is the distance from microphone 2 to sample;

$H_{12} = \frac{p_2}{p_1}$ is the transfer function which is the ratio of the Fourier-transform component between the sound pressure at position 1 and 2, k is the wave number.

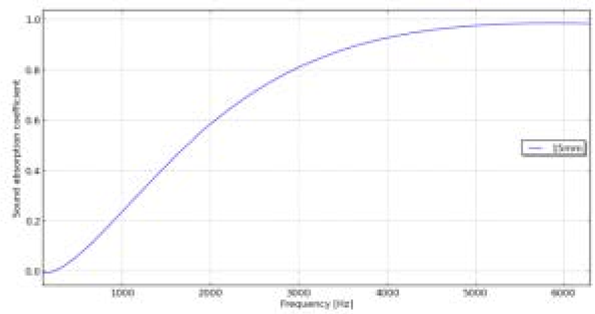

Fig. 7 - Sound absorption coefficient obtained by simulation for 15mm sample thickness

In Fig. 7 simulated material acoustic response is presented for 15 mm sample thickness. Simulation was performed based on Delany-Bazley empirical model in which an air flow resistivity of 27000 Rayls/m was defined as input data for acoustic material properties.

4.3. Step 3 - Comparative analysis

A closed-loop validation step was performed to investigate the correlation between the measured and predicted acoustical properties of materials. Results are obtained to assess the relationship between absorption coefficient, thickness and frequency response. Comparative analysis is performed to determine differences given by the approaches.

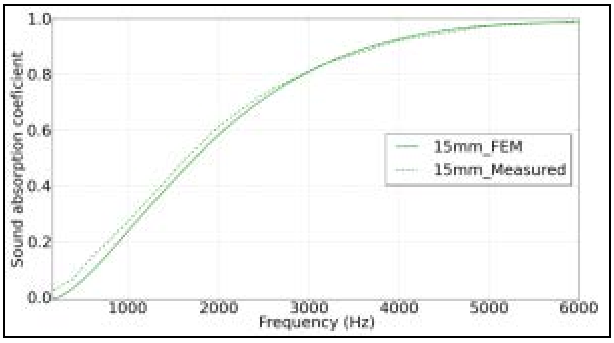

Fig. 8 - 15mm sample comparison between simulated and experimental measured results

Figure 8 presents the results obtained by numerical simulation and experiments 15 mm sample thickness and a good correlation is observed, the difference between methods being of 5%.

In general, the Kundt tube measurements are useful for fundamental research and for new product development, because the measured values for the acoustic absorption coefficient of a phono-absorbent material consider the physical properties of the material (flow resistivity, porosity, elasticity and density), results having a high accuracy degree. The differences obtained between experimental and numerical simulation can be explained by the fact that the empirical model used for numerical simulation does not take into account all these material parameters.

The results from both methods are very close; the differences observed are from the imperfection of the samples and the way of mounting the samples inside the tubes.

4.4. Step 4 - Relationship between absorption coefficient, thickness and frequency response

Step 3 shows that the Finite Element Method offers accurate results and it can be used in order to reduce the time spent with the preparations and the signals processing.

The present work purpose was to estimate an empirical relationship between absorption coefficient, thickness and frequency response, in order to perform a preliminary evaluation to reduce the options that could be taken into account for a more detailed research.

Due to the similarity between the simulated and experimental curves, one can say that the numerical model is suitable for studying other thickness of the tested material. In order to assess the relationship between absorption coefficient, thickness and frequency response for different material sample thicknesses was simulated, data being presented in Fig 9.

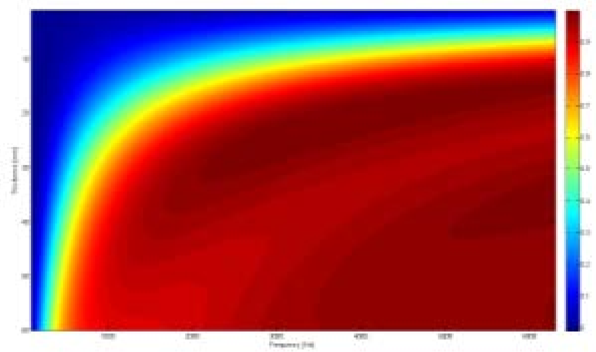

Fig. 9 - Relationship between absorption coefficient, thickness and frequency response for different material sample thicknesses

5. Conclusions

In designing solution to reduce noise is important to maintain a balance between cost and performance, the article study being important for learning more about the correlation between measured and simulated sound absorption coefficient depending on the sample thicknesses. Numerical simulation pays an important role in keeping reduced costs to evaluate the acoustic properties of materials considering specific applications.

This paper provides a simple reasonable methodology to assess the relationship between acoustic absorption coefficient, thickness and frequency response.

The purpose of the proposed methodology is to provide enough information to an investigator such that he can replicate the study along with the possibility to run different case studies, depending on the necessities.

References:

[1] M. DEACONU, L. CRISTEA; Sound transmission loss in porous and isotropic materials. Comparative analysis between impedance tube and FEM results; SISOM & ACOUSTICS 2016, Bucharest, pp. 12-13;

[2] A. Ravindran, Investigation of inverse acoustical characterization of porous materials used in aircraft noise control application, Thesis submitted to the Department of Mechanical Engineering and the faculty of Graduate School of Wichita State University in partial fulfilment of the requirements for the degree of Master of Science, 2004, pp.79-82;

[3] G. Lictra, L. Teti, F. Bianco, M. Cerchiai, FEM acoustical modelling of the impedance tube for improving road porous pavement behaviour description, Inter.noise, 2012, New York, pp. 6;

[4] M. Deaconu, Comparative analysis of transfer function and standing wave methods in determination of acoustic absorption coefficient, SISOM & ACOUSTICS 2014, Bucharest, pp. 302- 308;

[5] Sound Research Laboratories Ltd; 1990; Noise Control in Industry, Sound in Rooms; third edition, ISBN 0-203-78218-6, Taylor& Francis e-Library, Subury, Suffolk, pp. 46-47;

[6] SR EN ISO 10354-2/2005 Acoustics. Determination of sound absorption coefficient and impedance in impedance tube Part2: Transfer-function method; standard;

[7] Malcom J. Croker; 2007; Handbook of Noise and Vibration Control; First Edition; John Wiley & Sons, Inc.; New Jersey; pp. 32;

[8] X. Sagartzazua, L. Hervellab and J. M. Pagaldaya; Review in Sound Absorbing Materials; http://200.dm.fi.udc.es; pp. 48-62

[9] Actran User's Guide Vol. 1, www.fft.be;

[10] X. Sagartzazua, L. Hervellab and J. M. Pagaldaya; Review in Sound Absorbing Materials; http://200.dm.fi.udc.es; pp. 34-36;

[11] J.F. Allard and N. Atalla, Propagation of Sound in Porous Media: Modelling Sound Absorbing Material, second edition, John Wiley & Sons Ltd, 2009,United Kingdom; pp. 20-23;