

Measurement of Airflow Resistivity Variation Due to Temperature and Its Impact on Simulated Sound Absorption Inside a Vehicle's Passenger Compartment

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ABSTRACT

Airflow resistivity is one of the most important parameters in the study of the physical properties of porous acoustic materials. This parameter is fundamental for the correct evaluation of sound absorption of acoustic materials and is needed in all the theoretical models.

In the present work, airflow resistivity of porous materials is determined under effective operating conditions inside a vehicle (temperature, compression of the panels). Starting from the discussion on the measurement uncertainty, experimental data of airflow resistivity, measured as a function of temperature and applied static loads, are presented. By introducing the measured values in a SEA model of a typical vehicle panel, the foreseen values of acoustic absorption due to variation of temperature and static load are determined and presented.

1. INTRODUCTION

Design for noise control is today mandatory for every new successful product.

New cars and more in general new equipments must withstand maximum external noise emission and minimum internal noise comfort requirement; new buildings face every year with more strict requests for noise insulation.

Acoustical materials play an important role in noise control; engineers and architects must deal not only with Young

modulus and yield strength, but also with characteristic impedance (Z) and complex wave number (γ). These two global parameters define the acoustical behavior of a material and can be evaluated if some more "physical" parameters of the material are known.

The airflow resistance (AFR) is the most important "physical" parameter that permit to evaluate Z and γ (for the empirical models based on the Delany-Bazley formulas, it is the only one).

This is the main reason for the joined effort between FGA E&D (Fiat Group Automobiles Engineering and Design), INRIM (National Institute of Metrological Research of Turin) and Politecnico di Torino, spent during the last three years, to critically evaluate methods and associated uncertainty in measuring the AFR.

The present work will focus on the effect of temperature on the AFR value, and its influence on the simulated sound absorption coefficient α of selected components of the acoustic package of two Fiat vehicles. Other aspects of the AFR measurements have been discussed in previous works [1] [2].

The variation of the AFR due to temperature is used to assess the acoustic absorption of the hood insulator, while another exercise has been done on the inner dash panel, in order to predict the noise variation inside the car due to temperature variation.

The activity is part of a project in the NVH department of FGA E&D that aims to understand (and minimize) the causes of relevant variations of acoustical customer level measurements, due to apparent small differences in boundary conditions (temperature, humidity, tolerances, etc).

Over the years, in many papers and books the knowledge of the physical properties of porous and fibrous materials has been widely investigated. However, the airflow resistivity sensitivity to environmental parameters, particularly temperature, seems to be less known, at least from an experimental point of view. Similar experiments can be found in [3] and, more recently, on permeability evaluation as a function of temperature, are reported in [4]. The knowledge of the possible variability of the airflow resistivity under conditions of variable temperature is of interest for many specific applications. Airflow resistivity in sound absorbent materials can vary considerably depending on environmental conditions, varying as a consequence the acoustic behavior.

In this paper are reported the experimental results, on about twenty different samples of commercial materials, of the behavior of the airflow resistivity determined in a climatic chamber at different steps of temperature. Measurements are carried out by using an apparatus specifically designed to operate in variable conditions of temperature and humidity in a climatic chamber. The apparatus of measurement presented here was designed and realized at the National Institute of Metrological Research of Turin. A simple empirical method for estimation of the airflow resistivity as a function of temperature it is also proposed.

2. FUNDAMENTAL PHYSICAL THEORY

2.1. THE AIRFLOW RESISTIVITY DEFINITION

The classical methods for experimental determination of the airflow resistivity of materials used in acoustic applications, are established in ISO 9053 [5] and ASTM C-522 [6] Standards. These Standards describe the measurement equipment and the test procedure. The airflow resistivity of a material is defined as:

$$r = \frac{\Delta p}{q_v} \cdot \frac{A}{d} \quad [Pa \cdot s \cdot m^{-2}] \quad (1)$$

where:

- Δp is the air pressure difference across the sample with respect to the atmosphere, in Pa ;
- q_v is the air flow rate through the sample, in $m^3 s^{-1}$.
- A is the section of the tested sample, in m^2 ;
- d is the thickness of the tested sample (considered as homogeneous) in the flow direction, in m .

The airflow resistivity is of particular interest because gives a value of specific airflow resistance for unit of thickness, assuming an homogenous nature of the material. The airflow resistance, and the quantities directly correlated such as the specific resistance and the resistivity, depends on the characteristics of the material, on the properties of the gas that passes through it, and on the interaction between the structure of the material and gas.

In literature there are very detailed studies on the dynamic behavior of gas through porous and fibrous materials, e.g. [7,8,9,10,11,12,13]. The research presented here is focused in particular on the experimental determination of the temperature dependence of airflow resistivity.

2.2. THE INFLUENCE OF TEMPERATURE ON AIRFLOW RESISTIVITY

In extreme synthesis, it can be said that the temperature variation influences resistivity measurement mainly for two reasons: variation of the air viscosity and thermal expansion of the material under test. In first analysis, on the basis of the Poiseuille law, for which the resistance that a flow rate meets through a capillary, in a low frequency range [14], is directly proportional to the fluid viscosity, it is possible to trace a purely indicative proportion of the variation of the airflow resistivity in function of temperature T :

$$r(T) \propto \frac{8\eta(T)}{a_{eq}^2(T)} \quad [Pa \cdot s \cdot m^{-2}] \quad (2)$$

where:

- η is the coefficient of dynamic viscosity of air at temperature T , in $Pa \cdot s$;
- a is the radius of the capillary at temperature T , in m .

It is evident that, on the basis of this simplified relation, with the variation of temperature, airflow resistivity proportionally varies with the variation of air viscosity. Also the capillary radius a is subject to variation in function of the thermal

expansion coefficient of the material of which is constituted. Elementary kinetic theory of gases shows that the coefficient of viscosity is proportional to $T^{1/2}$, where T is the absolute temperature, but the temperature dependence is more complicated.

The equivalent radius of the pore a_{eq} is a quantity that expresses the average radius of one only pore in the material (i.e. the size of the relative intrinsic permeability, K_i , of the sample: $K_i \propto \pi a_{eq}^2$).

In other terms, the airflow resistivity, for a flow moving with a slow steady velocity (Reynolds number less than 1), can be expressed through the Darcy law:

$$q_v = \frac{K_i}{\eta(T)} \cdot \frac{\Delta p}{d} \cdot A \quad [m^3 \cdot s^{-1}] \quad (3.a)$$

that implies:

$$r = \frac{\eta(T)}{K_i} \quad [Pa \cdot s \cdot m^{-2}] \quad (3.b)$$

where:

K_i is the intrinsic permeability of the sample, in m^2 .

The intrinsic permeability K_i is a fundamental property independent of the flowing fluid, but depending upon the structure of the porous or fibrous material only, such as pore size, pore shape and porosity among others. Over the years many works have found evidence that the permeability, of a same porous material, may vary with different gases, and that is always higher than with liquids, with the respect to the Darcy law.

Permeability (then, as a consequence, airflow resistivity) of porous media also varies as a function of temperature, as observed by [4]. A possible explanation, as reported by the authors, could be due to the thermal slip coefficient, that occurs for the temperature [15].

Anyway it is difficult to observe experimentally the existence of the slip or of the thermal slip coefficient, in particular in complex system such as the porous or the fibrous materials and then quantify the losses due to the frictional phenomena inside actual materials.

With the purpose to interpret the structural complexity of the materials, characteristic quantities of the pores have been introduced by Johnson et al. [16] and by Champoux and Allard [17], such as tortuosity, characteristic thermal length and characteristic viscous length. These quantities permit to

describe in thermodynamic terms the flow dissipation phenomena inside an actual material. Nevertheless, from a purely experimental point of view, the determination of these quantities results particularly difficult [18] and may introduce uncertainties not easily controllable and/or identifiable.

3. MEASUREMENT EQUIPMENT AND EXPERIMENTAL METHODOLOGY

3.1. DESCRIPTION OF THE TEST APPARATUS

The airflow resistivity measurement equipment, shown in [Figure 1](#), performing measurement with alternate flow method, is characterized by:

- A cell measurement, diameter 100 mm;
- A perforated plate for the support of material, with a surface perforation $\geq 60\%$;
- A piston (Teflon®), diameter 50 mm, led by an eccentric connected to a micro-step motor, which produces a flow of air, alternating at 2 Hz;
- A 1" condenser microphone for the measurement of alternating pressure component in the closed volume of the cell;
- A measuring amplifier;
- A spectrum real-time analyser.

The airflow resistance measurement equipment has been put in a standard laboratory climatic chamber. Materials (steel for the cylinder and aluminum for the cell) used for the realization of the measurement apparatus allow the measures to be performed in a range of temperatures between -20°C and $+50^\circ\text{C}$ without suffering meaningful variations in operating capabilities due to thermal expansion. All the effect of the thermal expansion on the volume of the cell has been taken into account in measurement uncertainties.

- Aluminum thermal expansion coefficient: $0.000026 \text{ } ^\circ\text{C}^{-1}$;
- Area of test chamber at 20°C : 0.001924 m^2 , in a range of 70°C the variation is less than 0.1%;
- Volume of test chamber at 20°C : 0.001294 m^3 , in a range of 70°C the variation is less than 0.2%;

Nevertheless, measures have been carried out in a more restricted range of typically environmental temperature ($0^\circ\text{C} \leq T \leq 30^\circ\text{C}$), with constant relative humidity $U=(40 \pm 2\%)$. The samples under test, submitted to a static load of 250 Pa, have been conditioned for 2 hours for every step of temperature.

3.2. EXPERIMENTAL RESULTS

In [Table 1](#) the examined materials and the relative technical characteristics as mass, thickness, apparent density ρ_{app} , effective density of the material ρ_{eff} , porosity h and airflow resistivity r measured at 20°C according to the Standard ISO 9053 are presented. Porosity h has been calculated on the basis of the ratio between apparent density and effective density of the material.

On the basis of relation (2) and of materials properties showed in [Table 1](#), by knowing the airflow resistivity value measured at a certain temperature T (20°C in this analysis), it is possible to estimate the values of airflow resistivity at different temperatures by varying the value of dynamic viscosity and by calculating the variation of the pore radius in function of the thermal expansion coefficient of the tested material. The values of dynamic viscosity of air in function of temperature (with a relative humidity of 40%) and the surface thermal expansion of the tested materials are easily available in technical literature. The surface thermal expansion of the equivalent pore radius has been calculated from:

$$a_{eq} = a_m \left[1 - \frac{\alpha}{2} (T_x - T_m) \right] \quad [m] \quad (4)$$

Where:

- $\alpha/2$ is the surface thermal expansion coefficient of the material;
- a_m is the equivalent radius calculated at the measurement temperature T_m ;
- T_x is the temperature to which the effect of the thermal expansion is determined.

Airflow resistivity of all these materials has been therefore measured at 20°C and the equivalent radius, at the measurement temperature T_m , has been determined, on the basis of the relation (2), as:

$$a_m(20^\circ) = \sqrt{\frac{8\eta(20^\circ)}{r(20^\circ)}} \quad [m] \quad (5)$$

The values of equivalent radius, i.e. the size of the intrinsic permeability, for various steps of temperature have been therefore calculated, and airflow resistivity has been estimated following relation (2). It is important to notice that the reduction and/or increasing of equivalent radius obtained from relation (4) show a very small dependence from temperature (about 1.1%), then the effect of the thermal

expansion of the tested materials is not relevant on airflow resistivity variation.

The results have been compared with the measured airflow resistivity data in function of temperature, as shown in the graph of [Figure 2](#) and [Figure 3](#).

As it is apparent from the graph of [Figure 2](#) and [3](#), the relation (2) furnishes an already meaningful indication of the real behavior of airflow resistivity in function of temperature. Nevertheless, the angular coefficients of the curves estimated by following relation (2) and of the interpolated measured data present some systematic differences. With the increase of airflow resistivity, the dependence from temperature seems to be greater in comparison to what is estimated from temperature.

4. EMPIRICAL RELATION BETWEEN AIRFLOW RESISTIVITY AND TEMPERATURE

Angular coefficients of measured data have been calculated and compared with the angular coefficients of the prediction slopes deduced by relation (2). The increase of the angular coefficient of the interpolation slopes of the experimental data increases with a power law as a function of resistivity. The comparisons are reported in the graphs of [Figure 4](#). In the graph of [Figure 5](#) a zoom selection for values of airflow resistivity from 5 to 70 $kPa \cdot s \cdot m^{-2}$ is shown.

As it is possible to notice, the angular coefficients of the interpolation lines of experimental data and of estimated data on the basis of relation (2) are substantially comparable from 5 to 25 $kPa \cdot s \cdot m^{-2}$. In this range, resistivity as a function of temperature is dependent only from viscosity and density of the gas that crosses the test-sample and it seems that particular losses are not present.

Up to 25 $kPa \cdot s \cdot m^{-2}$ the effect of temperature on airflow resistivity becomes sensibility higher. As it is possible to notice, losses due to frictional phenomena are much more evident and the experimental results highlight a more severe increase of resistivity with temperature in comparison to values calculated by empirical relation (2).

On the basis of the experimental results trend, the angular coefficient of airflow resistivity data, as a function of temperature, increases within a power law as about 1.2th power, when airflow resistivity increases.

Once that airflow resistivity r_m of a material, measured at a certain temperature T_m , is known, it is possible to report it in the graphs of [Figure 4](#) and [Figure 5](#), according to the following simple relation:

$$r_x \approx r_m - (0.0025 \cdot r_m^{1.2}) \cdot [T_m - T_x] \quad [kPa \cdot s \cdot m^{-2}] \quad (6)$$

The validity of this formula has to be considered anyway limited for airflow resistivity r values between $5 \text{ kPa} \cdot \text{s} \cdot \text{m}^{-2}$ and $300 \text{ kPa} \cdot \text{s} \cdot \text{m}^{-2}$, in a range of temperatures between -10°C and 50°C . It is presumable that over the reported limits the proposed power law is not verified anymore. With regard to this, there are no specific and exhaustive experimental evidences.

5. THEORETICAL MODEL FOR THE SIMULATION OF SOUND ABSORPTION COEFFICIENT

To investigate sound absorption coefficient variations due to air flow resistivity change in the temperature range analyzed ($T=-10^\circ\text{C}$ to $T=50^\circ\text{C}$), a specific software developed by Rieter Automotive, named SISAB, has been used. This software has the purpose to represent acoustic absorption and transmission behavior of automotive materials.

The foundations of this program are based upon analytically derived transfer matrix representations of wave propagation through semi-infinite types of fluid, elastic solid, and limp, rigid and fully elastic porous material layers. Then, by using the respective transfer matrix representations of the various material layers, along with appropriate physical boundary conditions describing the interfaces between layers, a system matrix is constructed and solved for either normal incidence or diffuse field acoustic excitation.

The outcome is then the reflection, transmission, absorption and impedance quantities, which describe the acoustic behavior of the material. SISAB software makes use of this general approach to allow all types of automotive material configurations to be efficiently simulated.

In Chapter 3 it has been showed the effect of temperature variation on airflow resistivity measurements. Simulations has been done in order to understand if also acoustic absorption changes.

The starting point for the model creation is the definition of the component geometry, in this case the Alfa Romeo Giulietta hood insulator and the Alfa Romeo MiTo inner dash.

Subsequently, all materials with correct measured parameters and the layers which constitute the model are inserted. Since the physical component is characterized by different thickness areas (see [Figure 7.a](#), [7.b](#) and [7.c](#)), it is important to have the same thickness distribution in the model. So, a

thickness map is imported in the model and each layer is created in order to have a specific thickness. Finally, calculations are performed putting together all different layers, and acoustical parameters (absorption coefficient and transmission loss) are determined.

In [Figure 10](#) and [Figure 11.a](#) and [11.b](#), results of simulation are presented. In [Figure 8](#) the acoustic performance of the hood insulator panel is showed.

6. EXPERIMENTAL MEASUREMENTS ON CAR ACOUSTIC TREATMENTS

In order to correlate the resistivity variation due to temperature, with the acoustic absorption parameter of single panels of porous materials, experimental tests were conducted.

Samples coming from the hood insulator of Alfa Romeo Giulietta and from the foam of the inner dash panel of Alfa Romeo MiTo were measured according to the procedure described in Chapter 3.1.

Results of the test are presented in [Figure 9](#), were experimental data measured between 0 and 20°C are presented together with theoretical data derived from relation [\(6\)](#).

Experimental data were put in the model to estimate the variation of sound absorption coefficient of the hood insulator of Giulietta. Results of this simulation can be observed in [Figure 10](#), where separate evaluation of sound absorption coefficient with and without the air gap between the panel and the hood are presented.

In [Figure 11.a](#) and [11.b](#) are reported the simulated sound absorption coefficients of the inner dash panel, for the separate lower windshield cross beam and lower parts.

It must be considered that the front dash panel is in general constituted of two different materials: porous material and EPDM, and in current production components the acoustic property mainly affected is not sound absorption but transmission loss.

Nevertheless, in order to concentrate our study in the evaluation of the influence on sound absorption coefficient, this panel was simulated as if it was totally constituted of porous material. This simulation, that actually has more relevance from a methodological point of view, could in any case be used for future developments on new projects (i.e. light-weight and low-cost cars).