

On the Acoustic Impedance of a Fibreless Sound Absorptive Element

Fabio Auriemma and Heiki Tiikoja
Tallinn University of Technology

ABSTRACT

The acoustic impedance exhibited by a new type of element for noise control, the Micro-Grooved Elements (MGEs), has been widely investigated in this paper.

The MGEs are typically composed of two overlying layers presenting macroscopic slots and a number of micro-grooves on one of the contact surfaces. The micro-grooves result in micro-channels as the layers are assembled to form the element. Similarly to Micro-Perforated Elements (MPEs), the MGEs have been proved to provide effective dissipation of acoustic energy by the means of viscous losses taking place in the micro-channels. However, in contrast to the MPEs, the MGEs use the grooves, instead of the holes, in which the air is forced to pass through. It results in more cost effective elements, which have been found to represent an adequate alternative for fibrous materials, typically present in silencer units.

The design of the MGEs has been largely improved since the year 2012 and a number of configurations, provided with different internal geometries, have been produced during the last three years. For this reason new and more general models are needed, allowing to describe the acoustic behavior of those elements. In this study, the impedance model provided in the paper [1] has been extended and generalized in order to be applicable to a wider variety of MGEs configurations.

The methodology proposed here comprises a systematic investigation on the impedance contribution of all the constituting parts, e.g., inlet/outlet layers and internal micro channels, treated as series impedance. Experimental results have been carried out by extracting the transfer matrix from the 2-port data and by assuming constant particle velocity throughout the elements.

The acoustic impedance of the micro-channels has been studied in detail, since it gives the most important contribution to the global performance of the MGEs. Therefore, the impedance end corrections of the micro-channels have been determined by interpolating the impedance values of micro-channels with different lengths. Finally, the non-linear impedance contribution and the mutual interactions between the constituting parts have been experimentally evaluated and modeled by using ansatz equations.

CITATION: Auriemma, F. and Tiikoja, H., "On the Acoustic Impedance of a Fibreless Sound Absorptive Element," *SAE Int. J. Engines* 8(5):2015, doi:10.4271/2015-24-2462.

INTRODUCTION

The main problem related to the use of fiber and foam absorbers is the material deterioration and the consequent air pollution. When this issue became evident, initially mainly in room acoustics and HVAC applications, different solutions were proposed. During the last two decades, the research in applied acoustics has developed different fibreless materials which allow high broadband absorption coefficient while being light, thin, mechanically and thermally resistant.

As a matter of fact, traditional perforated metal plates - also known as distributed Helmholtz resonators - represent acoustic fibreless elements which have been widely studied and utilized since the 50s' [2]. However, especially in silencer applications, those elements have been usually utilized in combination with rock- or glass-wool, in order to overcome the low energy dissipation taking place therein.

In the 60s', micro-perforated elements (MPEs) were in focus in the studies of Maa [3]. It was shown that, by keeping a perforation ratio of the distributed Helmholtz resonators $\sim 1\%$, by reducing the aperture diameter and the plate thickness to the sub-millimeter range, high absorption coefficients were exhibited in 2-3 octaves frequency band. This behavior is related to the increase of viscous losses taking place in the small apertures where the boundary layer covers most of the cross sectional area.

Nevertheless, practical applications of MPEs were prevented by the high manufacturing costs, since laser cut process was typically needed to produce the small perforations. For this reason several fibreless acoustic solutions have been recently proposed aiming to exploit the same physical principles of the MPEs while reducing the production costs. Typical examples are represented by the low-cost MP absorbers with irregular slit-shaped apertures proposed by

Knipstein [4], the double layer perforated element proposed by Randerberg [5] and the micro-perforated insertion units proposed by Pfretzschner [6].

Plates with irregular slit-shaped apertures are difficult to model and present a noticeable surface roughness. Double layer perforated elements provide viscous losses in the gap between two perforated plates, but even sub-millimeter variation of this gap greatly affect the acoustic performance of the elements. Micro-perforated insertion units achieve a relatively low sound absorption peak (~ 0.8).

In 2012 MGEs were first presented in plate [7] and tubular [8] configurations and implemented in a locally reacting silencer for motorcycle applications [9]. The concept of MGEs is based on the use of engraved micro channels instead of passing micro-apertures. It allows replacing laser perforation process with cost effective and considerably less time-consuming burr removal process. The first modeling attempts were presented in [7] and [8], where also preliminary results about the impedance of the MGE in presence of grazing flow were included. In 2014, different MGE design configurations were presented in [1] and modeled by means of a semi-empirical approach with ansatz equations.

The present study aims to provide the ultimate design configurations of the MGEs and a more comprehensive impedance model. It allows accounting for the effects of a number of geometrical details, neglected in the previous works, by considering the influence of mutually interacting micro-channels and by offering a more general description of the non-linear effects.

DESCRIPTION OF THE MGE

The MGE (see Figure 1) is typically composed of two overlying layers presenting macroscopic slots and a number of micro-grooves on one of the contact surfaces. In contrast to the typical MPEs, the MGEs use the grooves, instead of the holes, in which the air is forced to pass through. Once the constituting layers are mated, such grooves form a number of micro-channels. In this way the sound waves enter the element via the slots of the first layer - the *inlet* -, pass through the micro-channels where dominant energy dissipation is expected to occur, and finally exit from the slots of the second layer - the *outlet* -.

The refined design of MGEs presented here consists of a *pseudo*-inlet layer made of a number of stripes connected to each other, thus partially covering the micro-grooves on the outlet and completely covering the slots of the outlet layer. This design allows manufacturing elements with a wide variety of micro-channels configurations (see Table 1) according to the desired impedance, while reducing the weight of the elements and simplifying the manufacturing process.

Table 1 presents the main geometrical parameters of the MGEs studied in this work. The thickness of every layer is equal to 1 mm, the width g of the outlet layer is equal to 4 mm. Element names

characterized by the same Greek letter are associated with samples provided with the same micro-channel length l . All the tested samples have 42mm diameter.

Samples with number from 001 to 029 are provided with small micro-channels (width $w=2.15$ mm) placed close to each other (distance $i=3.00$ mm), of the type in Figure 1a. In these samples, due to the small value of i , mutual interactions take place between adjacent micro-channels (c_1 and c_3 in Figure 1b).

Samples with number from 050 to 055 have wide micro-channels ($w=21.15$ mm), as in Figure 1b. In this case, there are no interactions of the type exhibited by the samples 001 to 029.

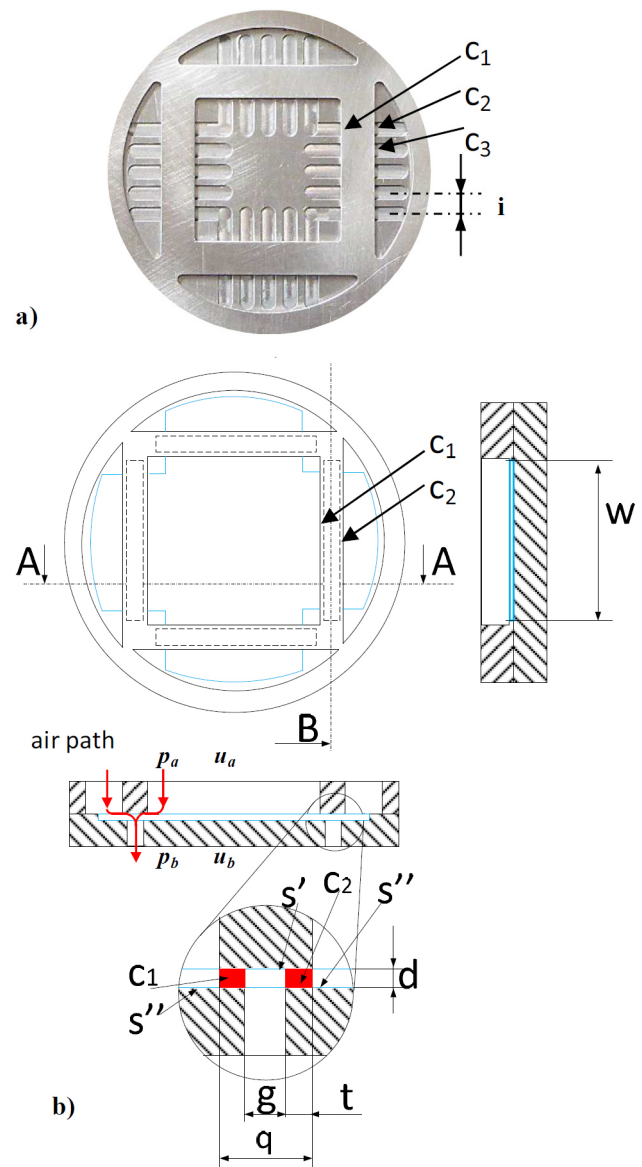


Figure 1. MGE. a) Photo of a sample provided with several mutually interacting micro-channels. b) Schematic representing the main geometrical parameters and the air path of a sample provided with wide micro-channels.

Table 1. MGEs tested

Sample name	Number of channels (n)	Depth of grooves (d) [m]	Length of micro-channels (l) [m]	Porosity (%)
001_α1-a1	40	3.15E-04	2.75E-03	1.96
002_α1-b1	32	3.45E-04	2.75E-03	1.71
003_α1-c1	28	3.45E-04	2.75E-03	1.50
004_α1-d1	24	3.36E-04	2.75E-03	1.25
005_α1-e1	18	3.42E-04	2.75E-03	0.96
007_β1-a1	40	3.12E-04	1.75E-03	1.94
008_β1-b1	32	3.45E-04	1.75E-03	1.71
009_β1-c1	28	3.42E-04	1.75E-03	1.49
010_β1-d1	24	3.33E-04	1.75E-03	1.24
011_β1-e1	18	3.39E-04	1.75E-03	0.95
013_γ1-a1	40	3.00E-04	1.25E-03	1.86
014_γ1-b1	32	3.45E-04	1.25E-03	1.71
015_γ1-c1	28	3.45E-04	1.25E-03	1.50
016_γ1-d1	24	3.36E-04	1.25E-03	1.25
017_γ1-e1	18	3.45E-04	1.25E-03	0.96
019_δ1-a1	40	3.15E-04	7.5E-04	1.96
020_δ1-b1	32	3.45E-04	7.5E-04	1.71
021_δ1-c1	28	3.45E-04	7.5E-04	1.50
022_δ1-d1	24	3.30E-04	7.5E-04	1.23
023_δ1-e1	18	3.51E-04	7.5E-04	0.98
025_ε1-a1	40	3.15E-04	7.5E-04	1.96
026_ε1-b1	32	3.30E-04	7.5E-04	1.64
027_ε1-c1	28	3.30E-04	7.5E-04	1.43
028_ε1-d1	24	3.30E-04	7.5E-04	1.23
029_ε1-e1	18	3.30E-04	7.5E-04	0.92
050_ε1-a2	8	1.36E-04	2.50E-04	1.35
052_ε1-a3	8	2.40E-04	2.50E-04	2.38
054_ε1-a4	8	3.64E-04	2.50E-04	3.62
055_ε1-a5	8	4.55E-04	2.50E-04	4.52

IMPEDANCE CHARACTERIZATION

The frequency band investigated in this paper is 100-3500 Hz. In this range the thickness of the element is much smaller than the wavelength. As a consequence, the normal particle velocity is expected to be constant in the MGE, i.e. $\mathbf{u}_a = \mathbf{u}_b = \mathbf{u}$ (see Figure 1b). All the samples have been exposed to six different levels of acoustic excitation, listed in Table 2, conventionally indicated as EL1...EL6 in this paper. The table includes the respective sound pressure levels (SPL) measured within the test duct in absence of samples (straight duct).

In general, the acoustic transfer impedance of a small aperture, Z_{tr-a} , is defined as the ratio between acoustic pressure drop Δp through the material and the normal particle velocity $\mathbf{u}$. The normalized transfer impedance, $z_{tr-a} = r + j\chi$ is equal to $Z_{tr-a}/(\rho c)$, where ρ is the air density and c is the speed of sound. Once Z_{tr-a} has been defined for one single aperture, the transfer impedance of the entire element can be written as: $Z_{tr} = Z_{tr-a}/\sigma$, where σ is the panel porosity.

The normalized transfer impedance is the acoustic parameter in focus in this paper. From the experimental point of view, under the hypothesis of constant particle velocity throughout the thin acoustic element, it can be shown that $T_{12}A$ represents the transfer impedance [11], where T_{12} is the first row second column element of the transfer matrix $\mathbf{T}$ of the sample and A is the cross sectional area of the sample.

For modeling purposes, in this paper it will be shown that Z_{tr} can be obtained by properly adapting, to the case of MGEs, the models developed by Allard [2] and Maa [3], for rectangular apertures, which are briefly summarized hereafter.

Impedance Decomposition

The impedance of acoustic elements provided with internal apertures can be decomposed in three parts: *internal part*, which includes the acoustic effects taking place within the apertures; *external part*, which accounts for the energy dissipation and air plug inertia taking place in the vicinity of the apertures. Finally, *non-linear part*, consisting of a modification of the external part occurring when the acoustic excitation exceeds certain limits.

For perforated plates with rectangular apertures, the above mentioned contributions of the impedance are known from the literature and are summarized here. The internal part is expressed by [2]:

$$Z_{slit-i} = \frac{j\omega t}{\sigma c} \left[1 - \frac{\tanh(k\sqrt{j})}{k\sqrt{j}} \right] \quad (1)$$

where ω is the angular frequency, t is the thickness of the plate, $k = d\sqrt{\omega/4\nu}$ the shear wave number, ν the kinematic viscosity of air and d the height of the slit. The external part is expressed by [2], [10]:

$$Z_{slit-e} = r_{slit-e} + j\chi_{slit-e} = \frac{4R_s}{\sigma \rho c} + j \frac{\omega d F(\bar{e})}{2\sigma c} \quad (2)$$

where $R_s = 0.5\sqrt{2\nu\omega\rho}$, $\bar{e} = \sqrt{1-(d/h)^2}$, $F(\bar{e}) = \int_0^{\pi/2} d\theta / (1 - \bar{e}^2 \cos^2 \theta)^2$.

The non-linear part is expressed as [2], [10]:

$$Z_{slit-NonLin} = r_{slit-NonLin} + j\chi_{slit-NonLin} = \frac{|u_h|}{\sigma c} + j\chi_{slit-e} \left(1 + \frac{|u_h|}{\sigma c} \right)^{-1} \quad (3)$$

where $|u_h|$ is the absolute value of the peak particle velocity inside the apertures. Equation (5) is valid for pure tone excitation.

Although the micro-channels of the MGEs have rectangular cross section, as the apertures in the plates with slit shaped perforations, the complex geometry of the MGEs prevents utilizing the Eqs. 2 and 3.