23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

EVALUATION OF DISSIPATIVE SILENCERS EFFICIENCY IN TERMS OF ITS SOUND TRANSMISSION LOSS

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Abstract. *The absorbent materials are gerenally fibrous and they have the purpose to increase the efficiency of silencers. There are many works that involve purely reactive silencers without absorbent material. However, there are few studies that depict the acoustic behavior of silencers with absorbent material. The difficulty in studying this type of silencers is to characterize the acoustic properties of the absorbent material. The properties required for the evaluation of dissipative silencers are the acoustic characteristic impedance and the complex wave number of the traveling wave. This paper evaluates dissipative silencers through the Finite Element Method (FEM) in terms of its sound transmission loss. The absorbent material is characterized with an inverse methodology.*

Keywords: *FEM, silencer, absorbent material, acoustic impedance, complex wave number*

1. INTRODUCTION

Currently, the Brazilian fleet is estimated at 38.0 million automotive vehicles, (ANFAVEA, 2014). As a general rule, the automotive noises are low frequency and the silencers used to attenuate these noises are made by uniting several kinds of acoustic filters. There are two types of acoustic filters: reactive and dissipative. The first type is manufactured by association of the expansion chambers, resonators, labyrinths and perforated tubes. The other type, it is manufactured with the addition of absorbent material within their cavities, (Munjal, 1987; Selamet et al., 2014).

The absorbent materials are generally fibrous and they have the purpose of increasing the efficiency of acoustic filters. The silencers built with these two types of filters are called hybrids. There are many works that involve purely reactive silencers without absorbent material, (Selame et al.,1997, 1999 e 2003a; Barbieri et al., 2004; Wu et al., 2008; Poirier et al., 2011; Lima et al., 2011 e 2013; Yasuda et al., 2013).

However, there are few studies that depict the acoustic behavior of silencers with absorbent material. The related studies in the literature use the material characterized by Selamet et al. (2003b) or the empirical expressions of Delany and Bazley (1970). According to Lee (2005) the difficulty in studying this type of filter is to characterize the acoustic properties of the absorbing material. The properties required for the evaluation of dissipative silencers are: characteristic acoustic impedance and complex wave number of the traveling wave. This work evaluates the efficiency of nine hybrid silencers with the Finite Element Method (FEM) in terms of its sound transmission loss. The absorbent material used in the models is glass wool whose density equal to 90 kg/m^3 and acoustical properties is evaluated by an inverse methodology presented in a previous work (Lima et al.,2014a)

2. THEORY

The characteristic equation for the three-dimensional finite element domain was expressed by Antebas et al., (2013):

$$[\mathbf{K} - \omega^2 \mathbf{M}] \cdot \mathbf{p} = \mathbf{F} \tag{1}$$

where **p** is the vector to be solved using FEM with sound pressures in any acoustic domain point of the silencer in [Pa].

The matrices associated with Eq. (1) for the subdomain air, represented by subindex *a*, are

$\mathbf{K} = \sum_{e=1}^{N_e^a} \int_{\Omega_e^a} \nabla^T \mathbf{N} \nabla \mathbf{N} d\Omega_a$ is the inertial matrix evaluated on the domain $d\Omega_a$; (2)

$\mathbf{M} = \frac{1}{c_0^2} \sum_{e=1}^{N_e^a} \int_{\Omega_e} \mathbf{N}^T \mathbf{N} d\Omega_a$ is the stiffness matrix evaluated on the domain $d\Omega_a$; (3)

$\mathbf{F} = -j\rho\omega \sum_{e=1}^{N_e^a} \int_{\Gamma_e} \mathbf{u}_n \mathbf{N}^T d\Gamma_a$ is the forcing vector evaluated on the boundary $d\Gamma_a$; (4)

c_0 is the air sound velocity [m/s];
ρ is the air density [kg/m^3]
e is the finite element e of the acoustic domain;
N_e^a is the last finite element of the air acoustic domain;
$\mathbf{u}_n$ is the normal velocity on the boundary $d\Gamma_a$;
∇ is the gradient operator;
$\mathbf{N}$ are the shape functions.

The matrices associated with Eq. (1) for the absorbent material subdomain, represented by subindex *m*, are

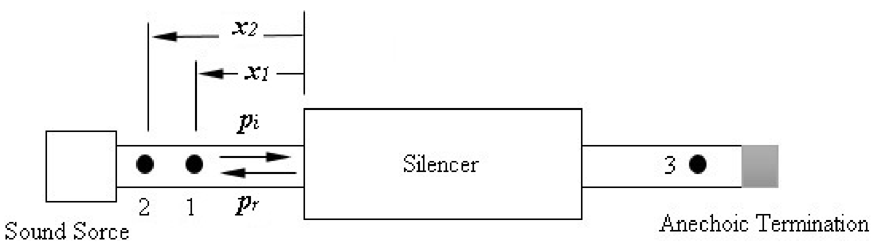
$\mathbf{K} = \sum_{e=1}^{N_e^m} \int_{\Omega_e} \frac{1}{\rho_m} \nabla^T \mathbf{N} \nabla \mathbf{N} d\Omega_m$ is the inertial matrix evaluated on the domain $d\Omega_m$; (5)

$\mathbf{M} = \sum_{e=1}^{N_e^m} \frac{1}{\rho_m c_m^2} \int_{\Omega_e} \mathbf{N}^T \mathbf{N} d\Omega_m$ is the stiffness matrix evaluated on the boundary $d\Omega_m$; (6)

$\mathbf{F} = \mathbf{0}$

N_e^m is the last finite domain element of the acoustic absorbent material;
$\rho_m = z / c_m$ is the complex density of the absorbent material [kg/m^3]; (7)
$c_m = \omega / k$ is the complex speed of sound [m/s]; (8)

Determining the pressure field (**p**) inside the silencer enables the assessment of its efficiency in terms of its TL via the Three-Point Method (TPM) developed by Wu and Wan (1995). Although this method is used for experimental analyses because of its simplicity, it can be easily used for computational analyses if the sound pressure at two points at the inlet and one point at the outlet are known, as shown in Fig. 1.



In this technique, two points at the input (points 1 and 2) and one at the output (point 3) are arbitrarily chosen. The sound wave at the inlet of the silencer has an incident portion and a reflected portion. At the outlet, if the termination is anechoic, the sound wave will have only the transmitted portion. Sound pressures at points 1 and 2 and the incident (p_i) and reflected (p_r) portions can be expressed as

$$p_1(f) = p_i(f) e^{+jkx_1} + p_r(f) e^{-jkx_1} \quad (9)$$

and

$$p_2(f) = p_i(f) e^{+jkx_2} + p_r(f) e^{-jkx_2} . \quad (10)$$

Solving Eqs. (9) and (10) for the incident and reflected sound pressure, we have

$$p_i = \frac{1}{2\mathrm{j}\cdot\sin[k_0(x_1 - x_2)]}\left(p_1 e^{-\mathrm{j}k_0 x_2} - p_2 e^{-\mathrm{j}k_0 x_1}\right) \tag{11}$$

and

$$p_r = \frac{1}{2\mathrm{j}\cdot\sin[k_0(x_1 - x_2)]}\left(p_2 e^{+\mathrm{j}k_0 x_1} - p_1 e^{+\mathrm{j}k_0 x_2}\right). \tag{12}$$

After determining the incident sound pressure using Eq. (13), the silencer TL can easily be obtained using the expression introduced by Munjal (1987):

$$TL = 20\cdot\log_{10}\left|\frac{p_i}{p_3}\right| + 10\cdot\log_{10}\frac{S_i}{S_0} \tag{13}$$

where S_i and S_0 are inlet and output cross sectional areas of the silencer ducts, respectively.

To apply Eqs. (5-8) on the study of dissipative silencers the correct specification of the acoustic properties of the absorbent material is needed (z and k), (Delany and Bazley, 1970; Lee et al., 2006a,b):

$$\frac{z}{z_0} = \left[1 + a_1\cdot(f)^{-a_2}\right] + \mathrm{j}\left[-a_3\cdot(f)^{-a_4}\right] \tag{14}$$

and

$$\frac{k}{k_0} = \left[1 + b_1\cdot(f)^{-b_2}\right] + \mathrm{j}\left[-b_3\cdot(f)^{-b_4}\right] \tag{15}$$

where

$\mathrm{j} = \sqrt{-1}$	is the imaginary unit;	
$z_0 = \rho c$	is the impedance characteristic of the environment [rayl];	(16)
$k_0 = \omega/c$	is the wave number of propagation [1/m];	(17)
$\omega = 2\pi f$	is the angular frequency [rad/s];	
f	is the excitation frequency [Hz];	
a_1, a_2, a_3 and a_4	are exponents to be determined for each type of absorbent material	
b_1, b_2, b_3 and b_4	are exponents to be determined for each type of absorbent material	

3. RESULTS

The efficiency of nine hybrid (dissipative) silencers with the Finite Element Method (FEM) in terms of its sound transmission loss (TL) are studied here, Fig. 1. The basic model has expansion chamber with internal perforated pipe. The perforated pipe has 10 rows with 12 holes equidistant each other with 5.0 mm of the diameter and its porosity is equal 8,1%. The chosen models have the chamber filled with absorbent material blocks in the longitudinal direction (see grey region in Fig. 1). In this work have not been studied models filled in the radial direction because this behavior has already been evaluated by Xu et al., 2004. The absorbent material used in the models is ordinary glass wool whose density is equal to 90 kg/m^3 and acoustical properties (z and k) is evaluated by an inverse methodology presented in a previous work, see Table 1, (Lima et al., 2014b).

The computational TL is calculated by Eq. (13) and the analyses proposed in this study use air at 20°C as the working fluid (stationary) with a specific mass ρ equal to 1.21 kg/m^3 and sound speed c_0 equal to 343 m/s. The finite element mesh was assembled with linear 4-node tetrahedral element.

In Table 2 are shown the dimensions of the computational models. Figures 3-5 show the comparison of TL for computational models proposed. In addition, in Fig. 5 is shown the experimental TL for model 7 which it was measured with the two source method (TSM), (Munjal and Doige, 1990). Briefly, the TSM consist of measuring the sound pressure at two points at the inlet duct and two points at the outlet duct of the silencer. These measurements are performed twice with two different impedances in silencer termination. The TL is obtained by manipulating the FRFs of the measured points with the first measuring point of the outlet duct as reference. The experimental apparatus scheme is shown in Fig 6.

Table 1. Exponents of the z and k, (Eqs. 14 and 15).

a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4
79,28	0,6146	97,70	0,6010	89,96	0,7569	54,78	0,7405

Table 2. Basic dimensions in (mm).

Model	L_1	L_2	L_3	d	D	Chamber
1	27,5	165,0	-	35,0	150,0	with wool and air
2	55,0	112,0	-	35,0	150,0	with wool and air
3	82,5	55,0	-	35,0	150,0	with wool and air
4	82,5	55,0	-	35,0	150,0	with wool and air
5	55,0	110,0	-	35,0	150,0	with wool and air
6	27,5	165,0	-	35,0	150,0	with wool and air
7	27,7	20,625	220,0	35,0	150,0	with wool and air
8	0	220,0	0	35,0	150,0	with air and without wool
9	110,0	0	0	35,0	150,0	totally filled with wool

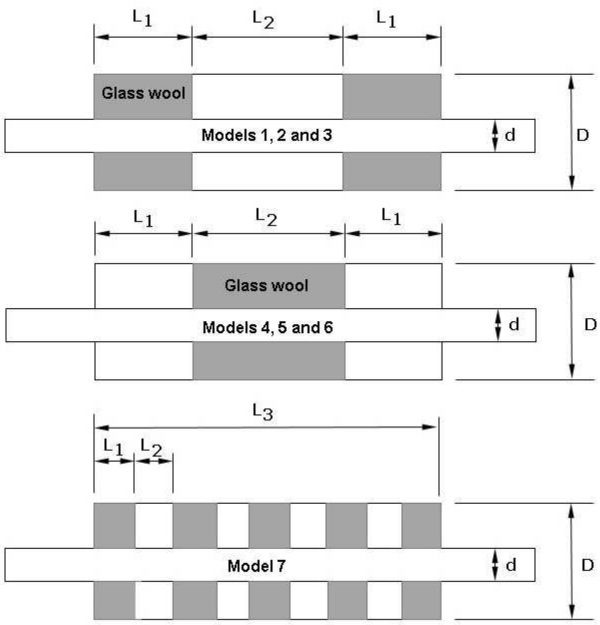


Figure 2. Dissipative silencers – computational models.

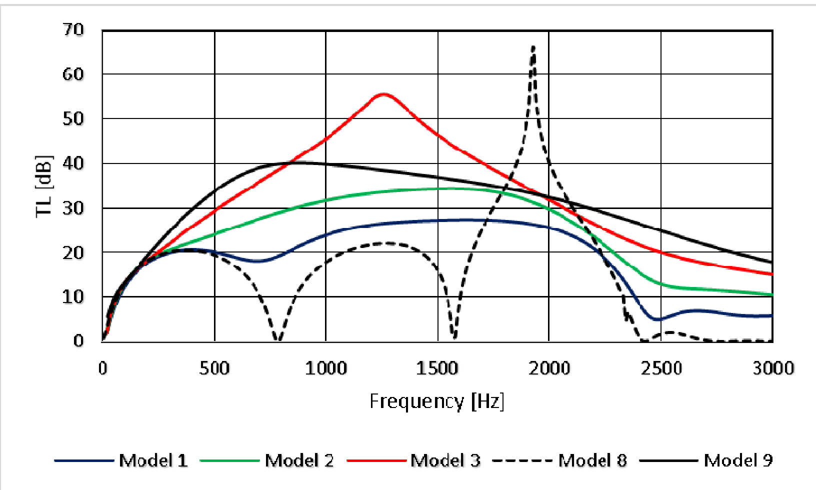


Figure 3. TL comparison for models 1, 2, 3, 8 and 9.

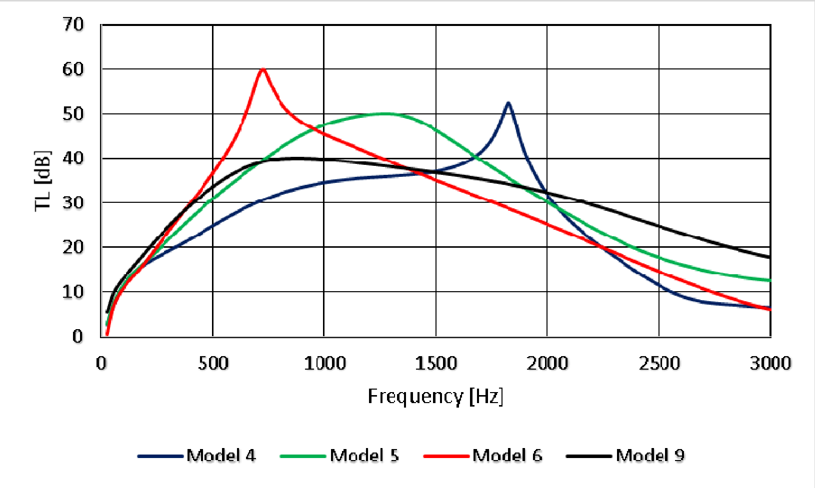


Figure 4. TL comparison for models 4, 5, 6 and 9.

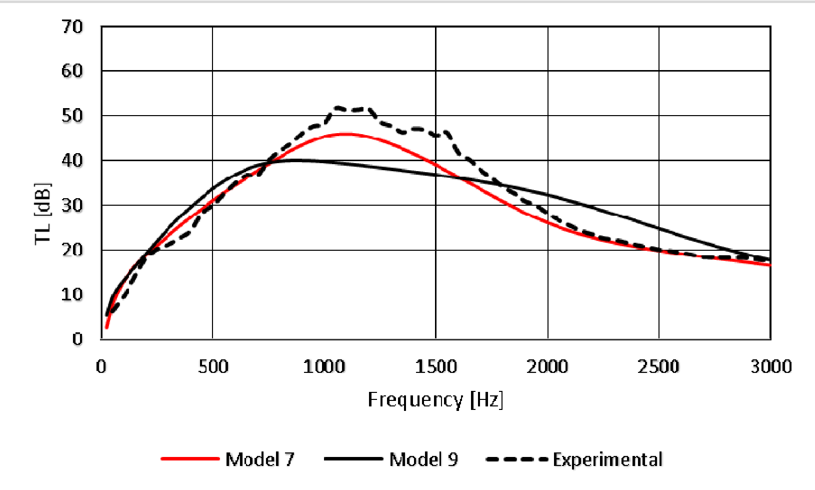


Figure 5. TL comparison for models 7, 9 and experimental.

Figures 3 and 4 show that acoustic efficiency of dissipative silencer increases with the amount of wool glass inside the chamber, as expected. Furthermore, based on the results, models 3 and 5 have a great efficiency when compared with model completely filled with glass wool (model 9). In general, the model 5 has a good efficiency with 50% of the chamber filled. This model is a good alternative for an economic dissipative silencer.

The experimental TL of the model 7 shows good concordance with computational result. The objective this experimental analysis is to verify the reliability of results by FEM.

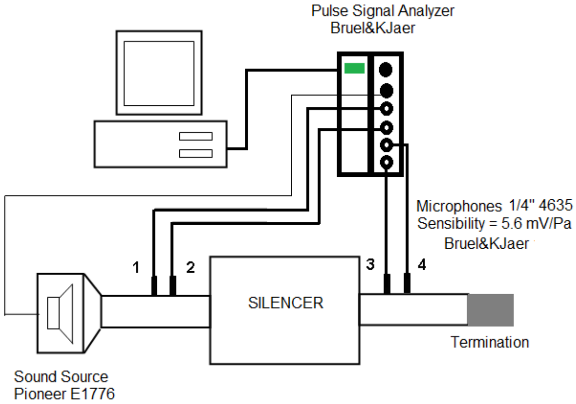


Figure 6. Experimental apparatus scheme.

4. CONCLUSION

The inclusion of absorbent material in the silencer chamber increases their acoustic efficiency. The models studied with glass wool arranged in blocks in the longitudinal position. The results showed that a central arrangement of wool with filling 50% of the chamber (model 5) has a good efficiency when compared to fully filled silencer.

5. ACKNOWLEDGEMENTS

This work had financial support provided by FINEP (Case No 0-1-11-0132-00).

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7. RESPONSIBILITY NOTICE