THE ACOUSTIC MULTI-CHAMBER MUFFLER PERFORMANCES

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Această lucrare studiază performanțele acustice ale unui atenuator de zgomot pentru trei cazuri speciale folosind tehnica numerică şi experimentală. Undele plane au fost la baza metodei matricilor de transfer (TMM) care poate oferi o soluție rapidă de prototip pentru proiectanții de atenuatoare. În această lucrare este prezentat principiul TMM pentru predictia pierderii prin transmisie (TL) pentru un atenuator de zgomot cu perforații. Metoda numerică de predicție este aplicată pentru fiecare configurație de atenuator de zgomot aleasă şi este comparată cu rezultatele obținute folosind sistemul de măsurare. Este considerat numai cazul staționar şi atenuatoarele de zgomot nedisipative.

This paper investigates the acoustic performance of a reactive silencer (muffler) for three special cases using numerical and experimental techniques. The plane waves based models such as the transfer matrix method (TMM) can offer fast initial prototype solutions for silencer designers. In this paper, the principles of TMM for predicting the transmission loss (TL) of a side-branch muffler are briefly presented. The method is applied for each silencer configuration and the numerical predictions are compared with the results obtained by means of an experimental setup. Only stationary, non-dissipative silencers are considered.

Keywords: silencer, transmission loss, transfer matrix method

1. Introduction

A silencer is an important noise control element for reduction of machinery exhaust noise, fan noise, and other noise sources involving flow of a gas. In general, a silencer may be defined as an element in the flow duct that acts to reduce the sound transmitted along the duct while allowing free flow of the gas through the flow passage. A silencer may be passive, where the sound is attenuated by reflection and absorption of the acoustic energy within the element. An active silencer is one where the noise is canceled by electronic feed forward and feedback techniques. In this paper, we will examine three cases of reactive (passive) silencers, also called mufflers, using numerical and experimental techniques. The detailed design procedures for mufflers are available in the literature (Munjal, 1987). [1]

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The **multi-chamber muffler** is a type of silencer used to reduce noise emission in a restricted frequency range from a mechanical system. This kind of muffler consists of a Helmholtz resonator connected to the main tube through which the sound is transmitted. The silencer acts to reduce sound transmission primarily by reflecting acoustic energy back to the source, so it is classed as a reactive silencer; however, some energy is dissipated within the acoustic resistance element of the silencer.

This paper investigates the acoustic performance of three configurations for the side-branch muffler with are shown in Figure 1, cases a, b, c.

The expansion chamber muffler consists of one or more chambers or expansion volumes which act as resonators to provide an acoustic mismatch for the acoustic energy being transmitted along the main tube.

Reactive silencers consist typically of several pipe segments that interconnect a number of larger diameter chambers. These silencers reduce the radiated accoustic power primarily counting on to the impedance mismatch, that is, by allowing the acoustical impedance discontinuities to reflect sound back toward the source. Essentially, the most relevant discontinuities are commonly achieved by: (a) sudden cross-sectional change (expansions or contractions), also by (b) wall property changes (transition from a rigid wall pipe to an equal-diameter absorbing wall pipe), or by (c) any combination thereof.

The use of a silencer is prompted by the need to reduce the noise radiated from a source but in most applications the final selection is based on some trade-offs among the predicted accoustic performance, the mechanical performance, the volume/weight ratio, and the cost of the resulting system.

The impact of the silencer upon the mechanical performance of the source is determined considering the change in the silencer back pressure. For a continuous-flow source, such as a fan or a gas turbine, the impact is determined from the increase in the average back pressure; by contrast, for an intermittent-flow source, such as a reciprocating engine, the impact is a function of the increase in the exhaust manifold pressure when an exhaust valve is open.

Most silencers are subject to volume/weight constraints, which also influence the silencer design process. In addition, the initial purchase/installation cost and the periodic maintenance cost are other important factors that influence the silencer selection process.

2. Silencer representation by basic silencer elements

Every silencer can be divided into a number of segments or elements each represented by a transfer matrix. The transfer matrices can then be combined to obtain the system matrix in order to predict the corresponding acoustical performance for the silencer system.

The procedure is illustrated by considering the silencer in Fig. 1, cases a, b, c, which is divided into the basic elements, labeled 1-11, indicated by the dashed lines.

Elements 1, 3, 5, 7, 9 and 11 are simple pipes of constant cross section.

Elements 2 and 8 are a simple area expansion, elements 4 and 10 are an area contraction with an extended outlet pipe.

Elements 6 represent a resonator connected through orifices, studied in three cases: a - for single line of perforated holes; b - for three line of perforated holes and c - for five line of perforated holes.

The eleven elements are characterized by the transfer matrices $T^{(1)}$ through $T^{(11)}$; therefore, the system matrix $T^{(S)}$ for this three particular cases of the whole silencer is obtained by matrix multiplication.

$$T^{(S)} = T^{(1)} \cdot T^{(2)} \cdot \ldots \cdot T^{(11)} \tag{1}$$

The matrices for each of the above elements may be derived from the formulas presented later in this paper.

Transfer matrices for each of these elements have been derived over the last three decades by different researchers, and explicit expressions for their four-pole parameters are given in detail by Munjal. [3, 5]

The variety of silencer elements and the multitude of elements per silencer result in numerous silencer configurations.

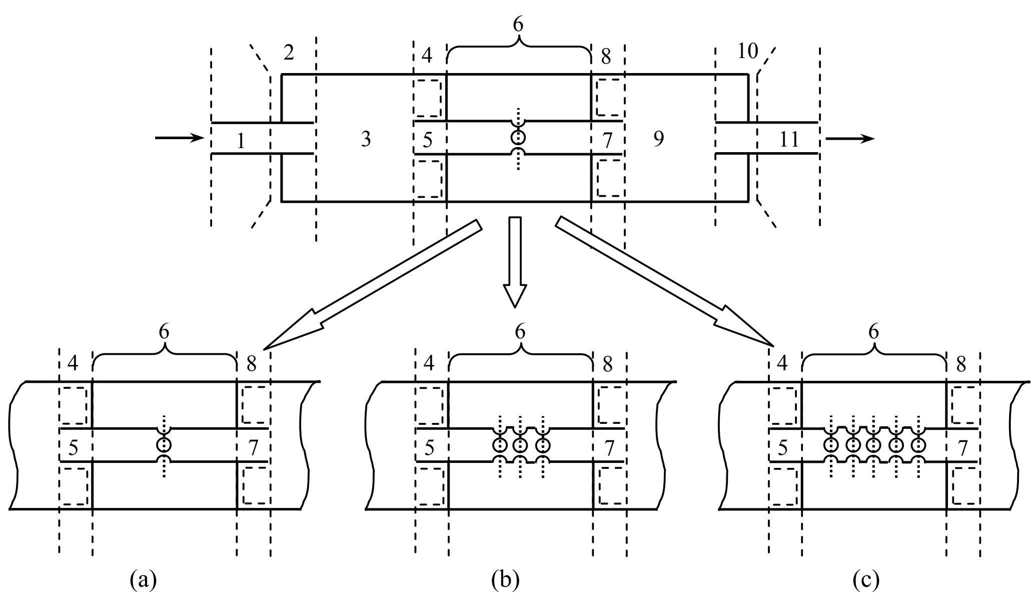


Fig. 1. Decomposition of silencer into basic elements for three-chamber configurations of perforated tube mufflers of concentric-tube resonator: (a) - for single line of perforated holes; (b) - for three line of perforated holes and (c) - for five line of perforated holes

3. Transmission loss for silencer elements

The transfer matrix method (TMM) use the transfer matrix of a silencer element as a function of the element geometry, state variables of the medium, mean flow velocity, and properties of duct liners, if any. The results presented below correspond to the linear sound propagation of a plane wave in the presence of a superimposed flow. In certain cases, the matrix may also be influenced by nonlinear effects, higher order modes, and temperature gradients; these latter effects, which can be included in special cases, are discussed qualitatively later in this section, but they are excluded from the analytical procedure described below. The following is a list of variables and parameters that appear in most transfer matrix relations of reactive elements: [3]

p_i = accoustic pressure at *i* th location of element

u_i = particle velocity at *i* th location of element

ρ_0 = mean density of gas, kg/m^3

c = sound speed, m/s, = $331\sqrt{\theta/273}$

θ = absolute temperature, $K = {}^{\circ}C + 273$

S_i = cross section of element at *i* th location, m^2

l_i = length of element *i*, m (Fig. 2)

$Y_i = c/S_i$

A, B = amplitudes of right- and left- bound fields

$k_c = k_0 / \left(1 - M^2\right)$ assuming negligible frictional energy loss along straight pipe segments

$k_0 = \omega/c = 2\pi f/c$

$\omega = 2\pi f$

f = frequency, Hz;

$M = V/c$ - mean-flow Mach number in exhaust pipe

V = mean flow velocity through *S*

T_{ij} = *(ij)* th element of transmission matrix of

Symbols without subscripts, such as *V*, *c*, and *M*, describe quantities associated with the reference duct.

For perforated tube mufflers in case of the element 6 include the following:

d_h = diameter of perforated holes (Fig. 3)

C = center - to - center distance between consecutive holes (Fig. 3)

The dimensions for length of elements ($l_1 \ldots l_{11}$) and diameters (d_i, d_e, D, d) use in the transmission matrix are show in Fig. 2. Here M_1 and M_2 represent the position of microphones.

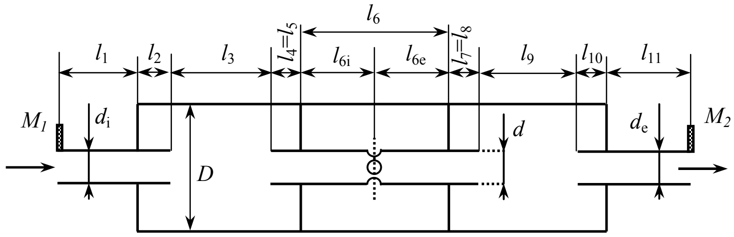


Fig. 2. Notation of dimensions

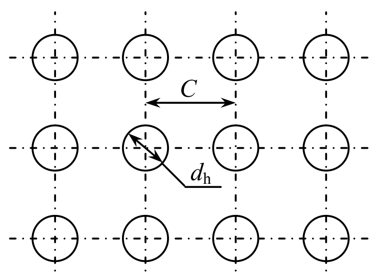


Fig. 3. Parameters d_h and C of perforated-tube walls

For **pipe with Uniform Cross Section** the accoustic pressure and mass velocity fields p_i, $\rho_0 S_i u_i$ in a pipe with uniform cross section S_i corresponding fields p_{i+1}, $\rho_0 S_i u_{i+1}$, we have [3,4,5]

$$\begin{bmatrix} p_{i+1} \\ \rho_0 S_i u_{i+1} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} p_i \\ \rho_0 S_i u_i \end{bmatrix} \tag{2}$$

where the transmission matrix T_{pipe} is given by

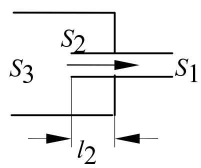
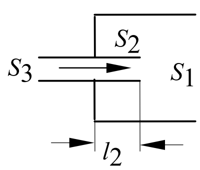
$$T_{pipe} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_{pipe} = e^{-jMk_c l_i} \begin{bmatrix} \cos k_c l_i & jY_i \sin k_c l_i \\ \dfrac{j}{Y_i} \sin k_c l_i & \cos k_c l_i \end{bmatrix} \tag{3}$$

For **Cross – Sectional Discontinuities** case, the transition elements used in modeling the cross-sectional discontinuities are shown in the first column of Table 1. Using decreasing element-subscript values with distance from the noise source, the cross-sectional areas upstream, at, and downstream of the transition (S_3, S_2, and S_1) are related through [5]

$$C_1 S_1 + C_2 S_2 + S_3 = 0 \tag{4}$$

Table 1

Parameter values of transition elements

Element Type	C_1	C_2	K
	-1	-1	$\dfrac{1-\dfrac{S_1}{S_3}}{2}$
	-1	1	$\left(\dfrac{S_1}{S_3}-1\right)^2$

where the constants C_1 and C_2 are selected to satisfy the compatibility of the cross-sectional areas across the transition.

Transfer matrices for cross-sectional discontinuities (csd) in the presence of mean flow that include terms proportional up to the fourth power (M^4) of the Mach number are presented in reference [5].

Components of the matrix T_{csd} is presented below [3]

$$T_{csd} = \begin{bmatrix} 1 & kM_1Y_1 \\ \dfrac{C_2S_2}{C_1S_2Z_2 + S_2M_3Y_3} & \dfrac{C_2S_2Z_2 - M_1Y_1(C_1S_1 + S_3K)}{C_2S_2Z_2 + S_3M_3Y_3} \end{bmatrix} \tag{5}$$

where

$Z_2 = -j(c/S_2)\cot k_0 l_2$

l_2 = length of the extended inlet/outlet pipe, m

Letting length l_2 tend to zero, yields the transfer matrix

$$\begin{bmatrix} 1 & KM_1Y_1 \\ 0 & 1 \end{bmatrix} \tag{6}$$

The transfer matrix for a resonator for a stationary medium is given by [3,4]

$$T_{st} = \begin{bmatrix} 1 & 0 \\ \dfrac{1}{Z_r} & 1 \end{bmatrix} \tag{7}$$

where $Z_r = Z_t + Z_c$, Z_t is the impedance of the throat connecting the pipe to the cavity, and Z_c is the impedance of the cavity. Here, Z_c is independent of the flow in the main duct and is given by the following expression:

$$Z_c = -i\frac{c}{S_6} \cdot \frac{1}{tgk_0 l_{6i} + tgk_0 l_{6e}} \; (m \cdot s)^{-1} \tag{8}$$

where $S_6 = \dfrac{\pi \cdot (D-d)^2}{4}$, and the lengths l_{6i} and l_{6e} are illustrated in Fig.2

The impedance Z_t of the throat connecting the duct to the cavity changes dramatically with grazing flow; therefore, it is characterized by two sets of values.

For $M = 0$, this quantity is given by [3]

$$Z_t^{[M=0]} = \frac{1}{n_h}\left(\frac{ck_0^2}{\pi} + i\frac{ck_0(l_6 + 1.7r_0)}{S_0} \right) (m \cdot s)^{-1} \tag{9}$$

where l_6 is the length of the connecting throat, r_0 the orifice radius, S_0 the area of a single orifice, and n_h the total number of perforated holes in the absence o mean flow.

The presence of grazing flow ($M \neq 0$ in the duct) has a strong effect on the impedance Z_t of the resonator throat [3]

$$Z_t^{[M\neq 0]} = \frac{c_0}{\sigma S_0} \cdot \left[7.3 \cdot 10^{-3}(1 + 72M) + i \cdot 2.2 \cdot 10^{-5}(1 + 51 l_6)(1 + 408 r_0) f \right] \tag{10}$$

where the parameters l_6 and r_0 are in meters and $\sigma = \dfrac{\pi d_h^2}{4C^2}$ is the porosity with parameters d_h and C from Fig. 3.

The transmission loss (TL) is given by [3,4,5]

$$TL = 20\,log\left|\frac{T_{11} + T_{12}/Y_1 + Y_{11}T_{21} + T_{22}}{2}\right| \tag{11}$$

4. Case study

The schema of the transmission loss setup in the absence of mean flow is show in Fig. 4.

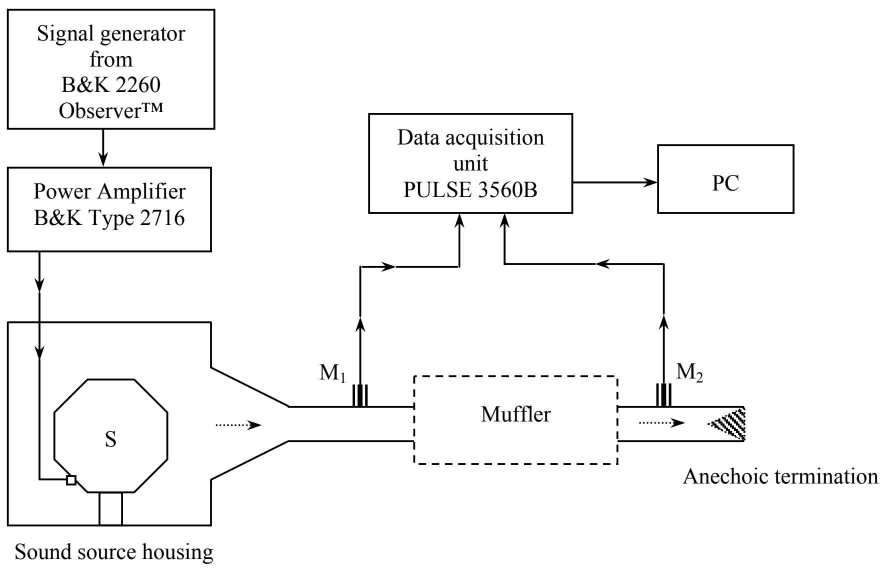


Fig.4. The schematic of the transmission loss setup in the absence of mean flow

where

S - OmniPower Sound Source B&K Type 4292

M_1, M_2 - 4188 1/2-inch Free-field Microphone, 8 Hz to 12.5 kHz

Dimensions of muffler elements (see Fig. 2) are presented below:

$l_1 = l_{11} = 0{,}095$ m, $l_2 = l_{10} = 0$ m, $l_6 = 0{,}4$ m, $l_{6i} = l_{6e} = l_6/2$

$l_4 = l_5 = l_7 = l_8 = 0{,}03$ m, $l_3 = l_9 = 0{,}27$ m

$d_i = d_e = d = 0{,}1$ m; $D = 0{,}4$ m, $d_h = 0{,}01$ m, $C = 0{,}031$

PULSE™ 3560B sound and vibration analysis system from Brüel & Kjær together with FFT and CPB Analysis Type 7700 software were used during the experimental tests for noise signal analysis (see Fig. 4).

A pink noise generator from B&K 2260 Observer™ and a controlled level sound source, B&K Type 2716 provided the acoustic excitation of Omni Power Sound Source for the test configuration (see Fig. 4).

a. b.

Fig.5. Test stand for mufflers

In Fig 5, two pictures are presented: one from the moment of assembly for one of the situations (Fig. 5 a) and a general picture of the test stand (Fig. 5 b) for measuring the transmission loss for multi-chamber muffler.

High performance condenser microphones were placed in M_1 and M_2 measurement positions for sound pressure signals capture.

Test results are presented below as TL spectral representation derived from the M_1 and M_2 signals spectra considering a low frequency range up to about 2,5 kHz.

In the diagrams from Fig. 6, 7, 8 are comparatively presented the predicted values obtained by formula 11 [3] and the experimental results of the transmission loss for three assembly cases:

- with a single line of perforated holes (see Fig. 6);
- with three line of perforated holes (see Fig. 7);
- with five line of perforated holes (see Fig. 8).

The predictive theoretical values are presented in Fig 6, 7 and 8 with dashed line; the calculus of values was perform with a MATLAB program, therefore the notation – "*Matlab model"* is use. In the same figures, for the experimental values we made a FFT analysis of those in-out two signals and are presented transmission loss between 0 and 2500 Hz frequency range – named *"Experimental"*.

For a better understanding of the differences and the correspondence between the analyses of predicted results (*Matlab model*) and the experimental results a trendline curve (from Microsoft Office Excel) was add to the experimental values – *"30 per. Mov. Avg. (Experimental)"* which represents an average of 30 experimental values once with the built-up of frequency. These trendlines are used to graphically display trends in experimental data and to analyze problems of prediction (is also called *regression analysis*).

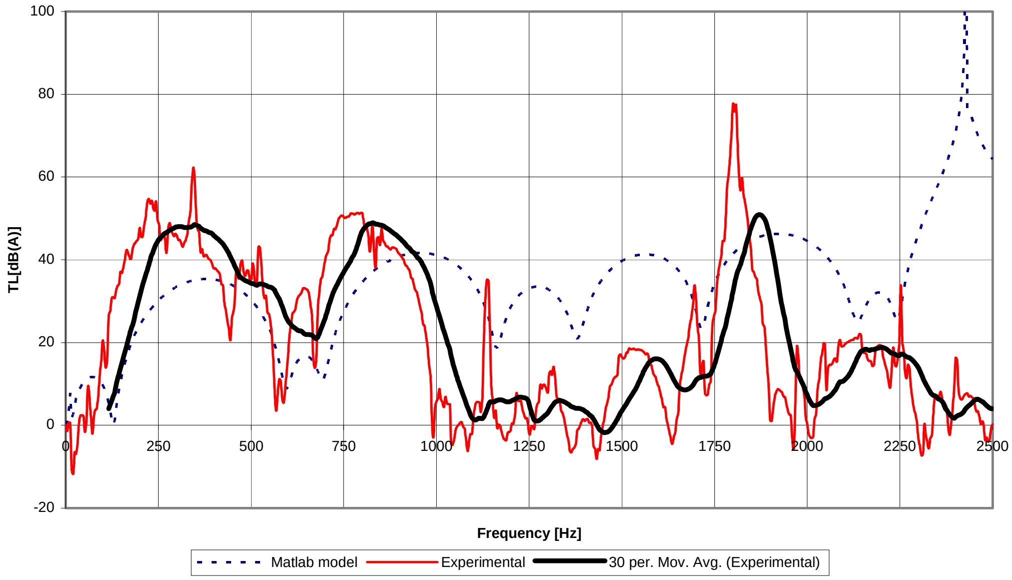


Fig.6. Transmission loss for muffler with a single line of perforated holes

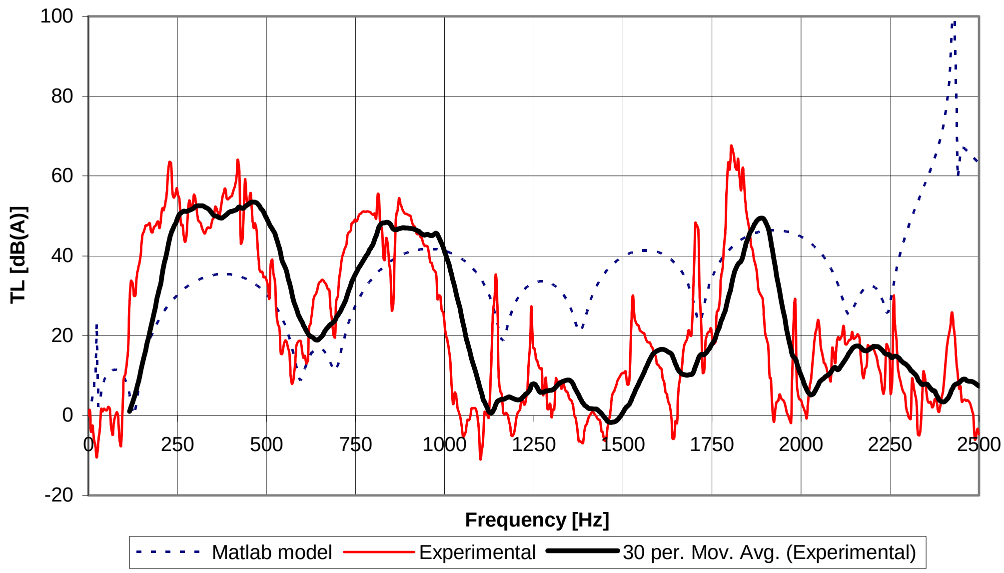


Fig.7. Transmission loss for muffler with three lines of perforated holes

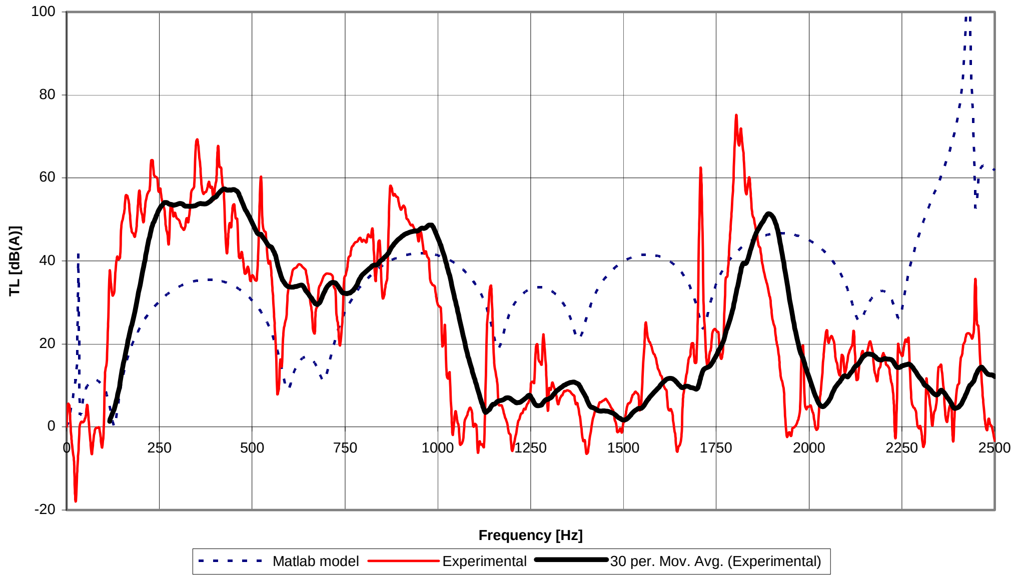


Fig.8. Transmission loss for muffler with five line of perforated holes

5. Conclusion

The results of theoretical and experimental analyse converge approximately only on 100-1000 Hz and 1750-1900 Hz, the rest of the domain have a considerable difference. The experiment was performed in good conditions, and we have observed all the rules concerning its development. We think the tests conditions were correct, but this type of silencer is usually utilized for attenuation of the gas flow noise, but in this case the flow speed was zero.

The conclusion that follows from the experiment and from calculus is: the five lines of perforated holes of muffler configuration provides considerably better TL values than the single line or three lines of perforated holes.

R E F E R E N C E S

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