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COMPARISON OF EXPERIMENTAL TRANSMISSION LOSS OF EXPANSION CHAMBERS MODELS WITH EXTENDED DUCTS AND MICROPERFORATED PANEL

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Abstract. *The use of microperforated panels in mufflers has presented as one of the ways to increase sound absorption properties and replace the use of fibrous materials in some applications. In expansion chamber mufflers, the combination of MPP with other geometrical changes, such as extensions of the inlet/outlet ducts, can provide different amplitudes of transmission loss, mainly in low-frequency bands. To demonstrate this performance four models of expansion chamber mufflers with microperforated panels have been proposed to operate in frequency ranges from 250 to 350Hz. These models combine the MPP position and the geometrical changes: an outlet extend duct inserted in the main chamber, internal partitions added to the MPP air cavity depth, and simultaneous inlet/outlet extend ducts. The acoustic performance of these mufflers was compared using the experimental TL via the Two Load Method (TLM). To validate the experimental results test bench was constructed and validated by the analytical method Transfer Matrix Method (TMM) and via the Finite Element Method (FEM) in the ANSYS software. In all models, the models presented TL with good performance in low and medium frequency ranges. The comparisons show that the addition of duct extensions at the inlet/outlet of the muffler was the principal influence on different TL amplitudes, indicating that the combination between the MPP and simultaneous extend ducts inside the chamber has a great potential for improving the TL of these mufflers, essentially to act at low frequencies.*

Keywords: *noise control, mufflers, microperforated panel, transmission loss.*

1. INTRODUCTION

Many factors motivate the use of reactive acoustic filters to noise control engineering, but they are essentially used when the applications requires highly hygienic conditions of the air. In these cases, it is strongly recommended the use of non-fibrous materials, in order to avoid the degradation caused by the effects like high temperatures or mean flow. Due to their simple structure and sound attenuation properties, the expansion chamber acoustic filter (ECAF) is a passive muffler usually applied in exhaust ducts. To enhance the acoustic performance of these elements, studies have been developed about changes in their internal geometry, with the purpose of enhancing your acoustic attenuation.

Selamet and Ji (1999) showed the effects of different lengths of extended inlet/outlet ducts on the ECAF, by its transmission loss (TL) curve, as a way to enhance its amplitudes. Yu and Cheng (2015) demonstrated the effect of various internal configurations in rectangular ECAF by inserted solid partitions in the main chamber, creating air apertures.

Perforated elements are often used in ECAF, as demonstrated in Ji (2008), behind inserted a perforated tube in a cylindrical model chamber, where the TL curve shows maximum values at lower frequencies. Although such elements present scarcely little inherent acoustic resistance, the use of micro-perforated panels (MPP) to enhance this property and ensure your performance as a good sound absorbent material, has been showing itself as a good alternative.

The MPP was initially proposed by Dah-You Maa (Maa, 1998), and consists in thin plates with perforations of sub-millimeter size (0.5-1mm) diameters, and 1% of perforation area. The acoustic performance of an reactive acoustic filter with MPP inside it has been shown to be similar to those in which fibrous materials are applied, even in systems that contain airflow (Allam and Åbom, 2011). Liu *et al.* (2007) showed the versatility of these elements and its application on the attenuated noise in exhaust ducts, according to the depth of air cavity, as an important property on the acoustical performance of MPP.

Some methods have been used to evaluate a TL of reactive acoustic filters with MPP inserted, like numerical and experimental techniques, in order to overcome the limitations existing by the analytical theory. The most common combination among the methods of obtaining TL is between Transfer Matrix Method (TMM) as analytical, Finite Element Method (FEM) as numerical, and Two Load Method, as experimental.

FEM is another numerical method widely used to simulate this type of silencer, presenting different aspects, where the representation of MPP can be given both by its geometry and by its acoustic properties, such as absorption coefficient and impedance (Jena and Panigrahi, 2015). Although there are many combinations between methods to obtain the TL, comparisons of the reactive acoustic filters with MPP inserted experimental TL and the way in which geometry changes influence this curve is still a research gap.

In this article comparisons between experimental TL curves of different models of reactive acoustic filters with MPP inserted are demonstrated, addressing the different ways that extended ducts can influence their acoustic performance. The extended duct should also be explored, concerning the TL curve and to enhance the application in ventilation and exhaust systems. The innovation of this study lies in the enable of reactive acoustic filters with MPP inserted to act in the low-frequency ranges (250 at 350Hz), which implies in mufflers with larger geometric dimensions. To improve TL curves essentially in low frequency range, is proposed the addition of geometric discontinuities on the expansion chamber models like variations on extended ducts and a MPP inside the main chamber.

2. METHODOLOGY

Figure 1 briefly represents the steps involved in the developed methodology. Due to mufflers size to act at low-frequency range, it was necessary to build a test bench that would enable the measurement of TL by the TLM. In order to validate the experimental TL a Simple Expansion Chamber (SEC) model was first designed, which in addition to being a model commonly used in exhaustion ducts, makes it possible to obtain the analytical TL in a simplified way. To this model the TL was determined by analytical, numerical and experimental methods, in order to validate the experimental results.

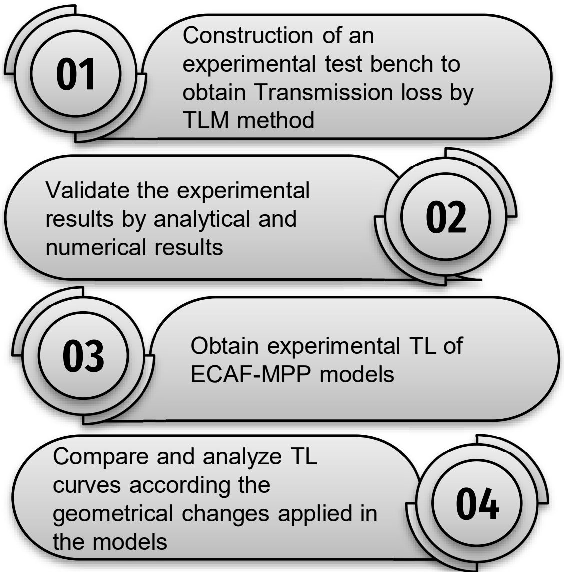


Figure 1. Summary flowchart of the methodology.

The analytical TL curve was obtained by the Transfer Matrix Method (TMM) which is based on the propagation of plane waves, that is, it is valid only up to the cut-off frequency of the SEC model. The numerical modeling of SEC was determined using the Finite Element Method (FEM) using the ANSYS© software.

The TL of an acoustic filter refers to the difference between sound power level incident at inlet and transmitted at outlet chamber, in presence of an non-reflexive termination in the outlet ducts of the chamber. It is obtained experimentally by the two-load method, whose mathematical development is based on the Transfer Matrix Method (TMM), where an acoustic filter can be modeled by its four-pole parameters, as shown in reference (Tao and Seybert, 2003) and experimental procedure is described by ASTM E2611 (ASTM, 2017).

In the experimental method to obtain the system transfer matrix, it is necessary to measure the sound pressure at four locations: two upstream and two downstream of the test object, which means the use of four microphones. Generally, one of these is used as a reference, so that the transfer functions between the microphones are measured in each test. This transfer function is a complex value, and is obtained between the reference microphone and the others. Thus, the four transfer functions are obtained, that is, four linear equations that will be used to solve the four parameters of transfer matrices that describe the system.

Thus, it is possible to obtain the transmission coefficient (τ) which consists of the dimensionless portion of the sound energy incident on the material that is transmitted and radiated to the medium, in a specific frequency range. Therefore, the experimental TL was obtained in terms of its τ, as it follows:

$$\tau = \frac{W_t}{W_i} \tag{1}$$

$$TL = 20\log_{10}\left|\frac{1}{\tau}\right| \tag{2}$$

Equation 3 is a simplified way of writing Eq. 2, and was the way used to obtain the analytical TL of the simple expansion chamber model (SEC) used here as a benchmark.

$$\mathrm{TL} = 10\log_{10}\left[1 + \frac{1}{4}\left(m - \frac{1}{m}\right)^2 \sin^2 kL\right]. \tag{3}$$

The $m = s_1/s_2$ is the ratio between the cross-sectional areas of the main chamber (S_2) and the inlet and outlet ducts (S_1), k is the wavelength and L the length of main chamber. Through this equation, the minimum amplitude values of TL (TL = 0) occur when $\sin kL = 0$, for this, $kL = n\pi$, that after replacing the wave number and manipulation between the variables, minimum frequency is given as $f_{min} = \frac{nc}{2L}$, when $kL = \frac{(2n-1)\pi}{2}$ and $f_{max} = \frac{(2n-1)c}{4L}$, with $n = 1, 2, 3...\infty$.

The MPP design to available its inserted inside the main chamber also combines the use of analytical theory Maa (1998) and numerical (FEM modeling) methods to obtain its absorption coefficient. With the validation between these techniques, the MPP model was inserted inside the acoustic filter models. The dimensions and geometry of the MPP used will be described in the section 2.2

The theory to describe the acoustic absorption performance of an MPP is given by reference Maa (1998), in which the normalized relative impedance (dividing by $\rho_0 c_0$)), as Eq. 4 and its real R and imaginary M parts can be obtained as described in Eq. 5 and Eq. 6, respectively.

$$Z_{\mathrm{MPP}} = (\mathrm{R} + j\mathrm{M})/(\rho_0 c_0) = r + j\omega m, \tag{4}$$

$$\mathrm{r} = \frac{32\eta t}{\sigma\rho_0 c d^2}\left[\left(1 + \frac{k_{\mathrm{p}}^2}{32}\right)^{1/2} + \frac{\sqrt{2}}{32}k_{\mathrm{p}}\frac{d}{t}\right], \tag{5}$$

$$\mathrm{m} = \frac{\omega t}{\sigma c}\left[1 + \left(1 + \frac{k_{\mathrm{p}}^2}{2}\right)^{-1/2} + 0,85\frac{d}{t}\right], \tag{6}$$

where η is the viscosity, t is the thickness of panel, σ is the area perforation ratio, ρ_0 is the mass density of air, c is the speed of sound (m/s), d is hole diameter, ω is the angular frequency ($\omega = 2\pi f$). The k_p is the perforate constant and is given by:

$$k_{\mathrm{p}} = d\sqrt{\frac{\omega\rho_0}{4\eta}}. \tag{7}$$

In order to be an effective absorption material, an MPP must be positioned in front of a support cavity, which is usually a solid surface or wall, and the interval between these two, compounds the air gap of the MPP. The impedance of air gap is given by Eq.8.

$$Z_{\mathrm{a}} = -\cot(\omega L_c/c), \tag{8}$$

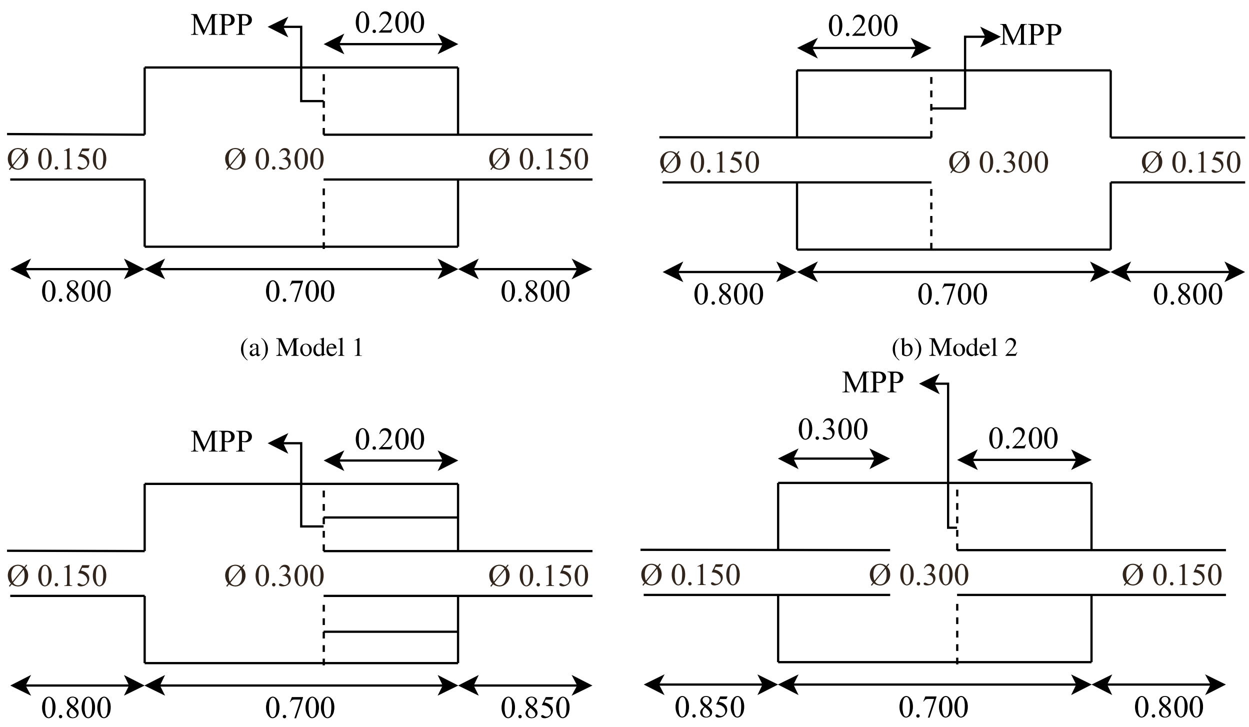
where $\mathrm{L_c}$ represents the length of air gap. Its value is increase in the imaginary part of the Z_{MPP}. Therefore, the total relative impedance of an MPP positioned in front of an air gap, is represented by:

$$Z_{\mathrm{T}} = Z_{\mathrm{MPP}} + Z_{\mathrm{a}}. \tag{9}$$

Thus, for normal wave incidence, the MPP absorption coefficient is given as a function of its relative impedance, according to Eq. 10, which was used both in the analytical and numerical parts to obtain the MPP impedance.

$$\alpha = \frac{4r}{(1+r)^2 + (\omega m - \cot(\frac{\omega L}{c}))^2} \tag{10}$$

With the validation of experimental test bench and MPP design, four reactive acoustic filters with MPP inserted models are proposed that combine extended ducts and MPP in the main chamber, as showed in Fig. 2, to know their acoustic performance. To facilitate comparisons, the geometry and dimensions of the models were plotted together with the TL graphics, in Section 3.Thus, the TL curves are compared regarding the insertion of MPP and geometries changes to verify how these influence the TL curves.



(a) Model 1 (b) Model 2

(b) Model 3 (b) Model 4

Figure 2. Models of reactive acoustic filters with MPP inserted.

2.1 Experimental test bench

First, to validate the experimental test bench used to obtain the TL of reactive acoustic filters with MPP inserted models, the circular simple expansion chamber model shown in Figure 3 is used.

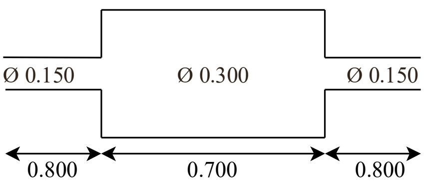
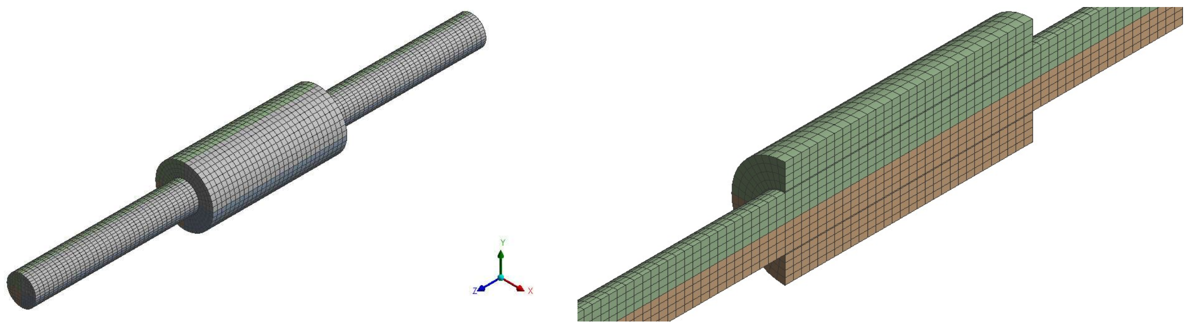


Figure 3. Simple expansion chamber model (SEC).

The dimensions of this muffler are adopted to allow its application in exhaust ducts up to 0.150 m in diameter, with a cut-off frequency of 670 Hz was used as the base model for the insertion of the different geometries that make up the reactive acoustic filters with MPP inserted models. The Finite Element Method (FEM) was applied to obtain the numerical TL, with 3D modeling in ANSYS®, as demonstrated in Fig. 4.



(a) Total view. (b) Cross section view.

Figure 4. Numerical model of SEC in ANSYS®.

In both methods, the same fluid properties were adopted, such as the temperature of 20 °C, air density $\rho = 1.21$ kg/m^3, the sound velocity of $343\ \text{m/s}$, and reference pressure of $2.10^{-5}\ \text{Pa}$. In the FEM model, boundary conditions were adopted referring to the excitation of system (sound source) as a plane wave incident on inlet duct of the chamber, with an amplitude of 1 Pa. To ensure that the numerical model had anechoic and a rigid termination of the output duct, as recommended by Tao and Seybert (2003).

Finally, the experimental TL was determined too, using the Two Load Method (TLM) in a constructed experimental test bench. Figure 5 represents the constructed test bench for TL measurements performed with the use of four microphones, before and after the muffler.

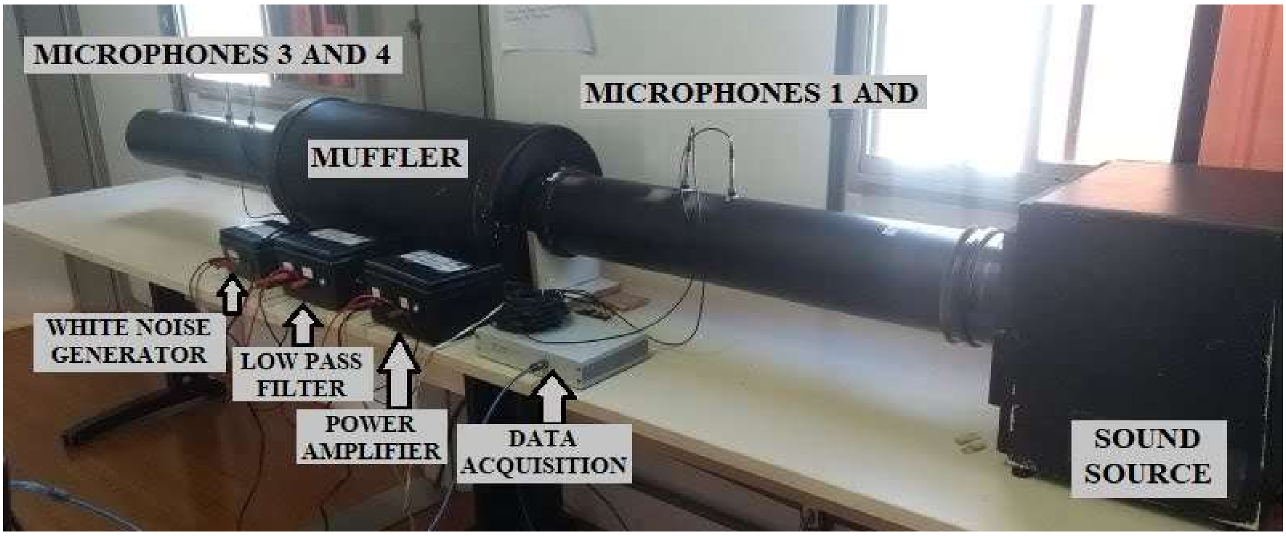


Figure 5. Experimental test bench constructed to measure TL of reactive acoustic filters with MPP inserted models.

To obtain the results, the muffler was positioned between four microphones with the VALab software acquisition system. The inserted signal was of the white noise generator, low-pass filter and a power amplifier, which were devices built in the laboratory itself in previous works by the research group Silva *et al.* (2013). For each model, TL measurements were made three times, the result being an average of the three measurements performed.

Figure 6 demonstrates the comparison of TL curves by analytical, numerical and experimental test bench, consolidating the experimental results with other methods of obtaining the TL.

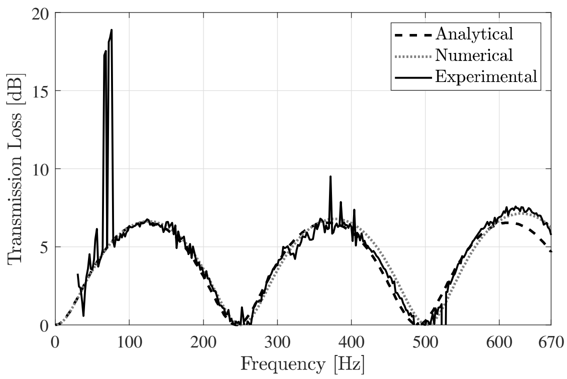


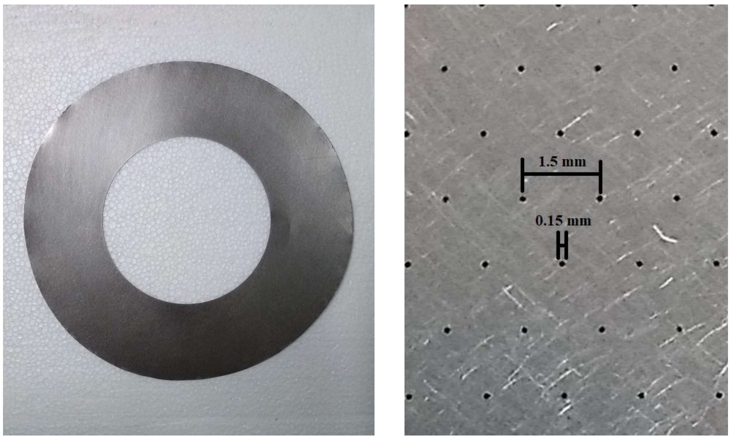
Figure 6. Comparison between the three TL curves for a simple expansion chamber model.

The comparison indicates that, in general, the experimental curve shows a good agreement between the numerical and analytical curves, consolidating the validation of the bench built between the two theories. In the lower frequency region, there are differences due to the limitations related to both the speaker and spacing between microphones adopted, which results in a low precision in this region. The numerical and experimental curves have a similarity as the frequency increases, in which the differences were about 1 dB between the analytical curve.

Although this model is widely used in exhaust noise control applications, with the dimensions adopted in this work for application in generator sets, it has low TL values. Considering that the way to improve this aspect is the addition of geometric discontinuities, expansion chamber models with extended ducts and MPP (reactive acoustic filters with MPP inserted) were proposed, as will be shown below.

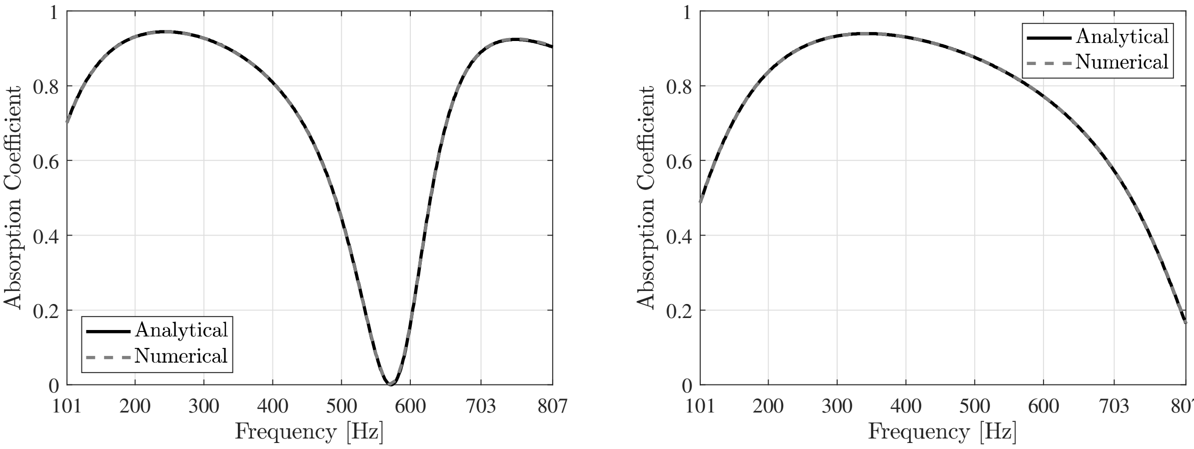
2.2 MPP Design

The design of MPP used in reactive acoustic filters with MPP inserted models was initialized by the analytical using the classical theory Maa (1998), and secondly by numerical model of its absorption coefficient using the Finite Element Method (FEM). As the SEC model, MPP was designed to operate as 250-350 Hz, with thickness, aperture and porosity of 0.18 mm, 0.15 mm and 0.79%, respectively. Therefore, figures x and y demonstrate the absorption coefficients found analytically and numerically for the different support cavity lengths which are L_1 and L_2, will be 0.3 m and 0.2 m, respectively.



(a) Total view. (b) Zoom on micro-perforations.
Figure 7. MPP used in reactive acoustic filters with MPP inserted models.

Figure 8 shows the manufactured MPP, in a total view of its geometry and an zoom of the micro-perforated area. The choice of this geometry belonging to it was motivated by its insertion inside the main chamber. So, MPP is positioned at the internal end of the inlet/outlet duct extension.



(a) Absorption coefficient of MPP with air cavity depth of L_1. (b) Absorption coefficient of MPP with air cavity depth of L_2.
Figure 8. Absorption coefficient of MPP according to cavity depth adopted.

3. RESULTS AND DISCUSSION

After the validation of experimental test bench, the comparisons and analysis of the results obtained begin. Therefore, comparisons of TL curves will be performed according to the variation of following parameters: extended ducts, internal partitions, and the simultaneous extended ducts with the MPP inside the chamber.

3.1 Insertion of MPP

In the acoustic performance of models without MPP, the inlet duct extension provides the formation of air cavities, which changes the propagation of sound in the main chamber. In Figure , the comparison between the TL curves demonstrates the combination between model 1, whose inlet duct length is L_1 = 0.2 m, with outlet duct extension, and then, with the addition of MPP inserted at the main chamber.

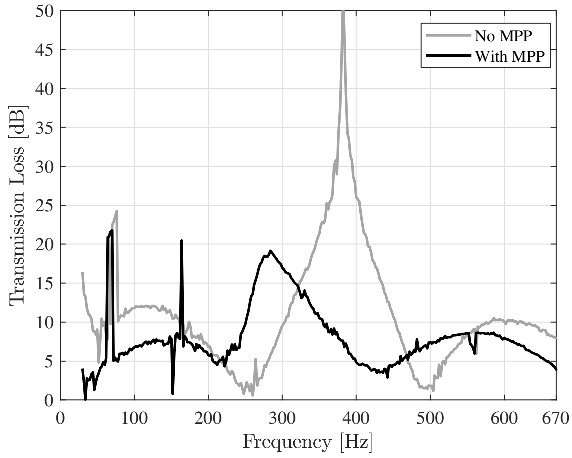


Figure 9. TL curve of model 1 before (gray line) and after (black line) MPP insertion.

The insertion of MPP inside the chamber showed a reduction in the TL peak amplitude, as demonstrated in Figure 9, the maximum value was reduced by about 17 dB. This means that adding the MPP does not increase the TL amplitudes, but changes the shape of TL curve in different ways, especially in conjunction with the extended ducts. Therefore, to better understand how the reactive acoustic filters with MPP inserted can present major TL amplitudes, several changes on the geometry were carried out, including positioning, length, and insertion of extended ducts, and even the addition of internal partitions in the air cavity of MPP.

3.2 Extend ducts

First, to analyze the position of MPP and extend ducts inside the chamber in TL values, the internal positions of the inlet and outlet ducts and MPP position are changed in models 1 and 2, where $L_c = 0.2\text{m}$ in both. Figure 10 shows a comparison between the TL curves of models 1 and 2.

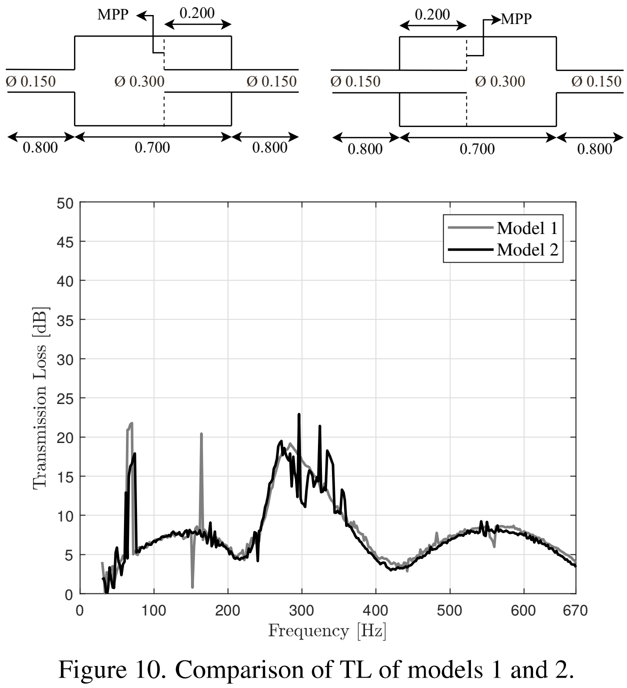


Figure 10. Comparison of TL of models 1 and 2.

The TL curve of model 1 was more accurate than the TL curve of model 2, which presents more fluctuations, this is due to the position of extended duct at the outlet, which gives greater precision and linearity to the TL curve. The maximum amplitude obtained by the TL curve of model 2 was 22.92dB, at 296 Hz. In the case of model 1, the maximum amplitude value is 19.16dB, at 284 Hz.

Differences between the curves indicate that the position of extended ducts and MPP at the outlet can provide more pronounced TL amplitudes. Although model 2 showed higher TL values, the accuracy of the curve obtained with the duct extension located at the outlet. This indicates that to achieve more precision in the TL curve for this mufflers, this type of internal configuration must be adopted, implying more exact values.

3.3 Internal partitions

The addition of internal partitions to the MPP air cavities, is a practice widely used to enhance its sound absorption, especially in acoustic filters. This is due to adding more geometry differences inside the main chamber providing more sound energy losses, which causes an increase in its acoustic performance Yu and Cheng (2015). These partitions were added parallel to the wall of the muffler chamber, as shown in Fig. 11, and consist of Model 3.

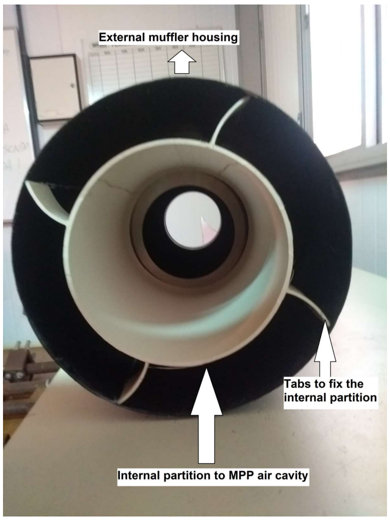


Figure 11. Muffler with internal partitions in the MPP air cavity depth.

Therefore, the partition was fixed to the internal wall of the chamber, and consist of a duct with a diameter of 0.2 m, according to the length of inlet or outlet duct, constituting a partitioned air cavity of MPP. Arranging the partitions parallel to the duct extensions provides effects that are still unknown among the studies of reactive acoustic filters with MPP Yu and Cheng (2015). For models with partitions and extension of the outlet ducts, the TL curves of models 1 and 3, shown by Figure 12.

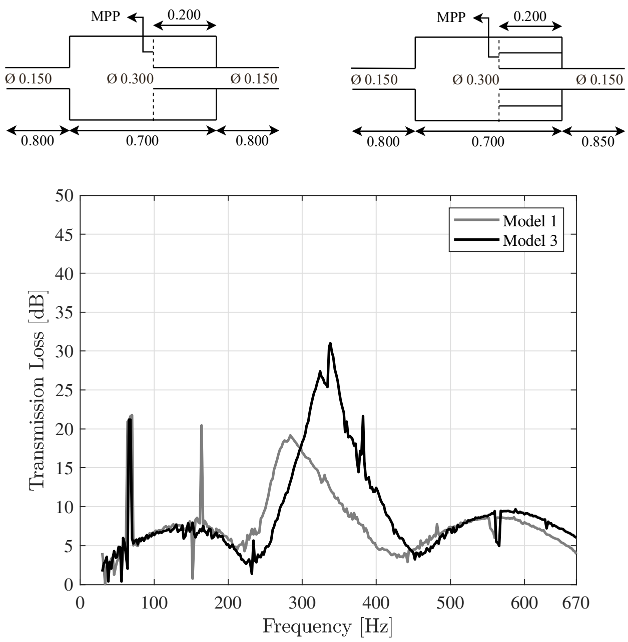


Figure 12. Comparisons of TL of models 1 and 3.

The TL curve of model 3 showed a greater amplitude by 12 dB, compared to model 1. Concerning frequency ranges, model 1 performed better at 284 Hz, with model 8 showing a maximum amplitude of TL at 338 Hz. This indicates the greater effect in TL values, after adding internal partitions. Therefore, it can be seen that the addition of internal partitions has a greater potential to influence the TL curves which means that with this geometry, the reactive acoustic filters with MPP inserted models will have a higher TL. Therefore, by adding internal partitions to the MPP support cavity and locating them at the exit of the expansion chamber, larger and more accurate TL amplitudes will be achieved.

3.4 Additional extended ducts

Another possibility for changes in the TL curves between models is the addition of an extension to the inlet or outlet ducts of the chamber with existing extended duct. With the same hypothesis where the chamber already has MPP positioned in front of the outlet duct with $L_c = 0.2m$, the TL curves of models 1 and 4 are compared, shown in figure 13.

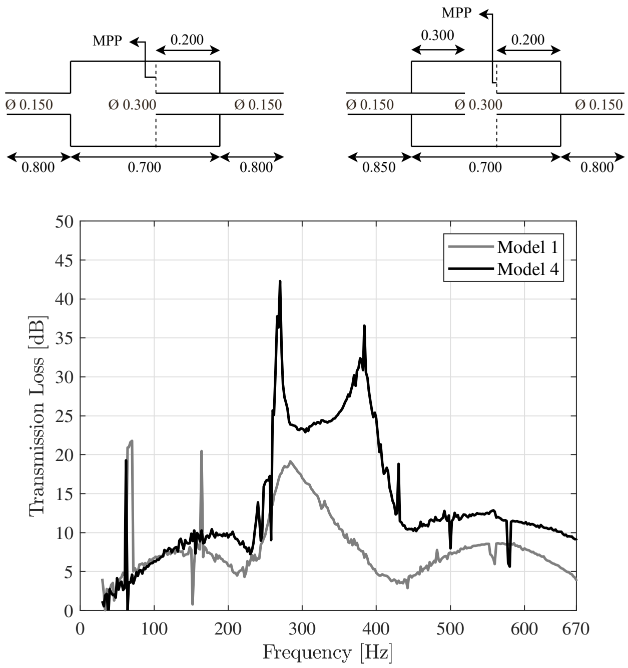


Figure 13. Comparisons of TL of models 1 and 4.

The addition of an extended duct at the inlet chamber also caused an increase in amplitude about the model that contains only one of the extensions. In this case, model 4 presented a maximum value of 42.3 dB at 270 Hz, presenting the second peak of 36 dB at 384 Hz. This indicates that in addition to a maximum value higher than model 1, it is possible to conclude that duct extension additions contribute significantly to increase the amplitude of TL curves of reactive acoustic filters with MPP inserted, and represents another way to achieve high TL amplitudes.

4. Conclusions

The present experimental study describes the acoustic performance of 4 expansion chambers with MPP inserted models according to its TL curves. The dimensions of these mufflers enables their application in passive noise control for exhaust ducts acting in a frequency range of 250 to 350Hz. The following items are the principal conclusions of the present study:

- Adding MPP, the magnitude of TL values was reduced, with the curve with MPP showing better performance in the low-frequency region. In comparison with the simple expansion chamber model, the insertion of MPP caused an increase in frequency range which it presented null values, demonstrating that there was a significant improvement in the acoustic performance.

- Regarding the position of ducts in internal chamber, the TL curves showed small differences in terms of amplitude and frequency peak. However, with the outlet extend duct, were founded more accurate curves.

- Internal partitions to the air cavity imply the most higher values of TL peaks with their small lengths and their location is in the outlet of chamber.

- The additional extended ducts in the inlet and outlet showed the most higher TL amplitudes among others models, indicating these additional ducts for increase the TL magnitudes in such models.

In general, with the insertion of MPP in the muffler, it is possible to predict the frequency ranges in which the acoustic filter can present higher TL amplitudes. However, the addition of extended ducts and internal partitions to MPP air cavity ensures increases in amplitude, and can also modify the frequency bands with better TL performance.

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