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Research Paper

Acoustic Silencer for a Dedicated Frequency

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Acoustic resonators are useful for damping low frequencies. In cylindrical silencers (mufflers), the implementation of the resonance concept consists in selecting such a length of the expansion chamber (EC) that a wave of opposite phase is created in it, and with this opposite phase the incident wave is damped. Based on the plane wave theory (1D) and simple analytical calculations, it is possible to approximately determine the shortest length of the EC for a selected frequency; such a chamber represents the simplest silencer. Its efficiency is measured by the transmission loss (TL) value; increasing the TL value indicates that the silencer efficiency increases as well. The efficiency was improved in two ways: first, in single EC, by adding inlet, outlet, or both horizontal extensions, and second, by adding another EC. In the first case, the influence of the length of the horizontal extensions on TL was analyzed. In the second study, another dedicated EC was added, and the influence of the width and orifice diameter of the transverse partition on TL was analyzed. All analytical results were confirmed experimentally. The results indicate that, first of all, a simple silencer (single EC) is found to damp a dedicated frequency. In addition, simple changes in the structure of such a silencer significantly increase its efficiency.

Keywords: acoustic silencer; transmission loss coefficient (TL); expansion chamber (EC); transverse partition; horizontal inlet/outlet extensions to a single D-EC.

1. Introduction

Acoustic silencers are used in many areas of live, e.g., in the automotive industry, HVAC ducts, and firearms (Munjal, 1987; Nilsson *et al.*, 2021; Karami *et al.*, 2024). They are mainly dissipative silencers, which work on the phenomenon of successive reflection of sound waves and the conversion of their energy into heat.

General requirements for the design of silencers are described in many studies (e.g., Potente, 2005; Rahman *et al.*, 2005; Munjal, 2013; 2014; Jokandan *et al.*, 2023). The desirable properties of a silencer are, above all, simple construction, small size and sound attenuation over a wide frequency range. To meet the first two requirements the main challenge is to reduce the volume of the silencer's expansion chamber (EC), in practice its length.

Generally, the effectiveness of a silencer is measured, by, e.g., the transmission loss (TL) coefficient (Lee *et al.*, 2020). There are many analytical and numerical methods to calculate TL (at the silencer design stage), as well as experimental TL measurements on a real silencer. Among analytical methods, 1D (in simple structures), 2D (cylindrical wave), and 3D (three-dimensional wave) theories are used. Also, numerical methods such as FEM/BEM (Selamet, Radavich, 1997; Strek, 2010; Cui, Huang, 2012; Wei, Guo, 2016) and computational programs, e.g., SYSNOISE, COMSOL, and ANSYS (Swamy *et al.*, 2014), are widely used. In the aforementioned methods, only the problem of reflection is taken into account, while other aspects of sound propagation in silencers are omitted (Rahman *et al.*, 2005). Three experimental methods are also used, i.e., the 'traditional' laboratory method, the four-pole transfer matrix method and the three-point method; they are compared in (Bilawchuk, Fyfe, 2003; Tao, Seybert, 2003; Zalte, Sature, n.d.).

The TL of a single circular EC can be increased through a variety of simple internal configuration. For example, the TL value was analyzed depending of the following parameters: EC length (Selamet, Radavich, 1997), surface absorption coefficient (Chiu, Chang, 2014), locations of horizontal partitions (Selamet *et al.*, 1998; Yu, Cheng, 2015), horizontal inlet/outlet extensions (Chaitanya, Munjal, 2011; Munjal, 2013; Rafique *et al.*, 2022), and also multi-chamber silencers with transverse partitions (Selamet *et al.*, 2003; Yu, Cheng, 2015; Yu *et al.*, 2015; Xiang *et al.*, 2016). In the mentioned studies, the influence of silencer structure on TL in a certain frequency range was considered.

The aim of this article is to demonstrate that it is possible to build a structurally simple silencer for a dedicated frequency, using of course conclusions from previous studies. This is important because, apart from starting and breaking, mechanical devices typically generate noise at an approximately constant frequency. Such a silencer should be therefore most effective at this dedicated frequency compared to other similar designs. Assuming that an objective function is TL, maximizing TL will indicate the optimal silencer for the dedicated frequency.

2. TL of the cylindrical EC

Due to the purpose of silencers, it is advisable to predict the maximum TL at the design stage. It turns out that the most important parameter is the geometry of the EC. For a given diameter of a cylindrical EC, the remaining task is to determine its length (Bilawchuk, Fyfe, 2003).

To define TL, we first define the sound power transmission coefficient (TC), $a_{\mathrm{tr}} = W_{\mathrm{out}}/W_{\mathrm{in}}$, where $W_{\mathrm{tr}} = W_{\mathrm{out}}$ is the outgoing (transmitted) acoustic power, and W_{in} is the incident (incoming) acoustic power. The TL is then expressed in terms of the TC (in dB) (Barron, 2003; Swamy *et al.*, 2014):

$$\mathrm{TL} = 10\log_{10}\left(W_{\mathrm{in}}/W_{\mathrm{out}}\right) = 10\log(1/a_{\mathrm{tr}}). \tag{1}$$

For a plane wave, at the inlet and outlet one has:

$$W_{\mathrm{in}} = \frac{p_{\mathrm{in}}^2}{2z_0}S_{\mathrm{in}}, \qquad W_{\mathrm{out}} = \frac{p_{\mathrm{out}}^2}{2z_0}S_{\mathrm{out}}, \tag{2}$$

where $z_0 = \rho c$ is the characteristic impedance, S is the surface area, p_{in} and p_{out} are the average (root mean square (RMS)) pressures at the inlet and outlet, respectively.

Hence,

$$\frac{1}{a_{\mathrm{tr}}} = \frac{W_{\mathrm{in}}}{W_{\mathrm{out}}} = \frac{p_{\mathrm{in}}^2}{p_{\mathrm{out}}^2}\frac{S_{\mathrm{in}}}{S_{\mathrm{out}}}. \tag{3}$$

Primary approach to sound transmission through the EC is the 1D theory (Selamet, Radavich, 1997; Barron, 2003; Tao, Seybert, 2003; Zhang *et al.*, 2020; Rafique *et al.*, 2022). After some calculations, the following useful equation is obtained:

$$\frac{1}{a_{\mathrm{tr}}} = \frac{1}{4}\frac{S_1}{S_3}\left\{\left(1+\frac{S_3}{S_1}\right)^2 + \left[\left(\frac{S_2}{S_1}+\frac{S_3}{S_2}\right)^2 - \left(1+\frac{S_3}{S_1}\right)^2\right]\sin^2(k_2\ell_2)\right\}, \tag{4}$$

where, see Fig. 1, $S_\nu = \pi r_\nu^2$, $\nu = 1, 2, 3$ are the cross-sectional areas of the inlet, EC, and outlet, and $u_{\nu,i}$ and $u_{\nu,e}$ denote the incident and reflected plane waves, respectively.

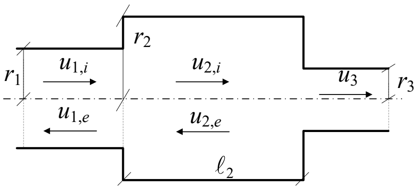

Fig. 1. Plane wave transmission through the EC.

Note that the TL, Eq. (1), reaches a maximum if $1/a_{\mathrm{tr}}$ is also a maximum. For this to happen, $\sin^2(k\ell_2)$ ought to be one. So:

$$k\ell_2 = \frac{\pi}{2} + n\pi, \qquad n = 0, 1, 2, ... \tag{5}$$

Hence,

$$\ell_2 = (1+2n)\frac{\lambda}{4}, \qquad n = 0, 1, 2, ... \tag{6}$$

The minimum chamber length $\ell_{\min}$ is for $n = 0$:

$$\ell_{\min} = \lambda/4 = c/(4f). \tag{7}$$

In this way, the minimal length of the EC is obtained, for which the TL reaches its maximum values. However, note that the 1D theory is valid only up to the 'cut off' frequency (Potente, 2005).

In fact, sound transmission through a single EC is somewhat different from what the 1D theory suggests. As indicated in (Kang, Ji, 2008; Chaitanya, Munjal, 2011), the difference between 1D analysis and experimental, 3D, or numerical analyses is due to the presence of three-dimensional waves. Therefore, as pointed out in (Yu, Cheng, 2015), the 1D model can be used to approximately calculate the TL maxima, but only if the cross-section of the EC is sufficiently small.

3. Numerical calculations and experiments

The construction of a structurally simple silencer for a dedicated frequency was realized in the following steps:

1) Based on the 1D theory, the minimum length of the EC was found. Due to the inaccuracies of

this theory, this length was then experimentally corrected, so the length of the dedicated expansion chamber (D-EC) was obtained.

2) The TL was increased by adding horizontal inlet/outlet extensions to a single D-EC.
3) The TL was further increased by adding another D-EC, which was achieved by adding a transverse partition to the corresponding EC length:
   - the influence of the transverse partition widths was determined at a fixed orifice diameter,
   - the influence of the transverse partition orifice diameters was determined at a fixed width.

All measurements below were performed using the Brüel & Kjær set, based on the four-pole matrix. They were conducted for frequencies $f = \{1,2,3,4,5,6\} \times 10^3$ Hz, while results were presented at selected frequencies, i.e., $f = \{1,3,5\} \times 10^3$ Hz.

3.1. *Attached length of the* EC → D-EC

The influence of the single EC length $l_{\min}$, Eq. (7), on the TL was analyzed, where

$$\ell_{\min} = \{8.5, 2.83, 1.7\} \cdot 10^{-2}\,\mathrm{m}.$$

Furthermore, the TL was calculated according to Eq. (1), using the following parameters: $r_1 = 0.003$ m, $r_2 = 0.018$ m, $r_1 = r_3$, hence $S_1 = S_3 = 2.827 \cdot 10^{-5}\,\mathrm{m}^2$, $S_2 = 1.0179 \cdot 10^{-3}\,\mathrm{m}^2$, $k_2 = k = (2\pi f)/c$, $\ell_{\min} = \lambda/4$. The results are presented in Fig. 2.

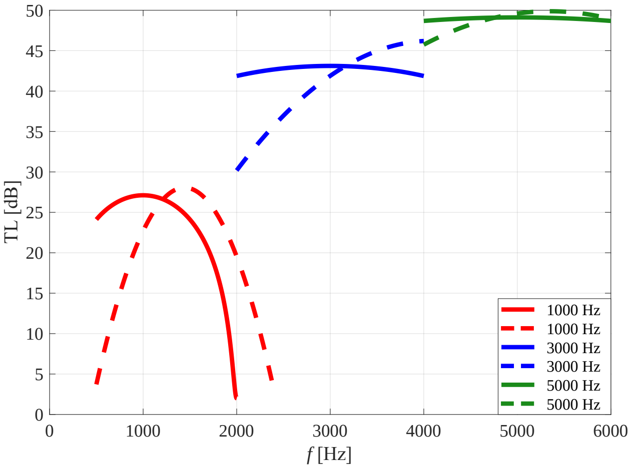

Fig. 2. TL for a single EC, solid line – calculated values Eq. (1); dashed line – measured values.

As can be seen in Fig. 2, the experimental results do not agree with the 1D theory, which predict the TL maximum occurs at the dedicated frequency. So, in order to account for the influence of three-dimensional wave effects, the length $\ell_{\min}$ ought to be increased by some length ℓ_a, so that the chamber length $\ell = \ell_{\min} + \ell_a$ corresponds exactly to a quarter-wave length; this adjusted length leads to the D-EC.

The attached length ℓ_a can be estimated based on numerical calculations, such as the finite element method (FEM) (Komkin *et al.*, 2012), or through theoretical considerations (Selamet, Radavich, 1997; Kang, Ji, 2008). In this study, ℓ_a was determined experimentally. For this purpose, the TL was measured as a function of frequency for different values of ℓ_a, Fig. 3.

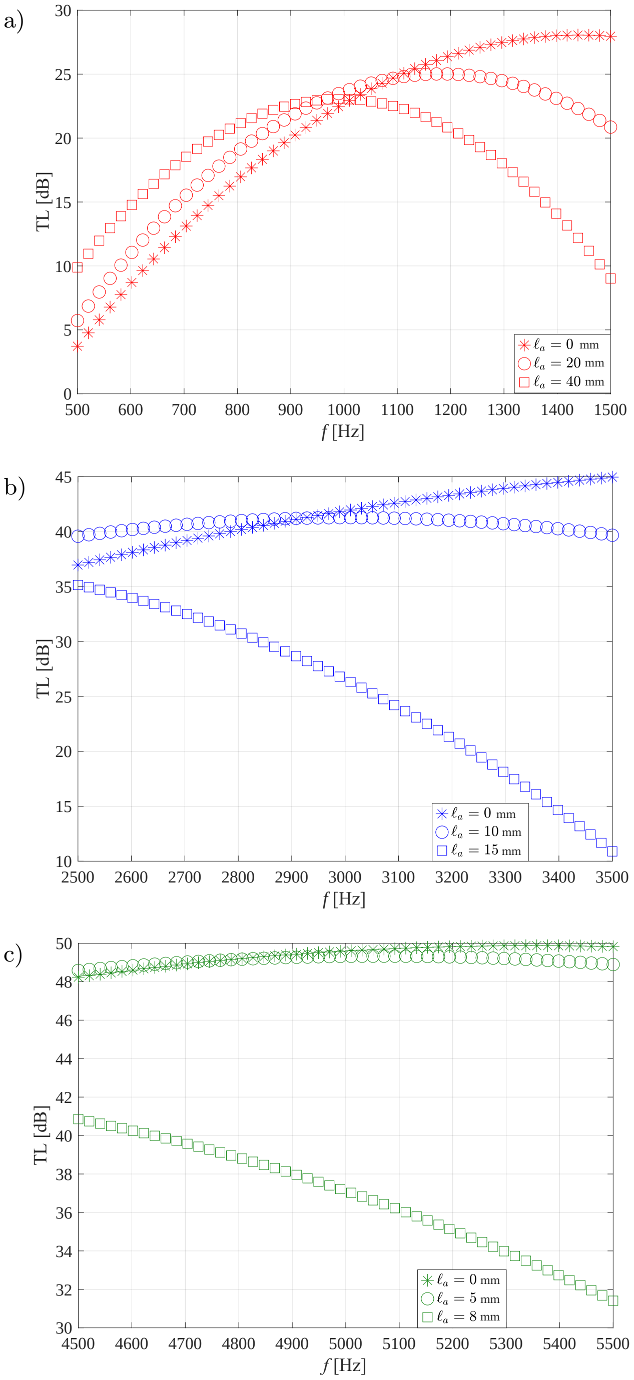

Fig. 3. Influence of different ℓ_a values on the maximum TL at selected frequencies: a) 1000 Hz, b) 3000 Hz, c) 5000 Hz.

For each frequency, the value of ℓ_a was chosen, which produced a TL value closest to its maximum. So, these results were $\ell_a = \{40, 23, 10, 7, 5, 0\}$ mm for $f = \{1, 2, 3, 4, 5, 6\} \times 10^3$ Hz, respectively. From discrete ℓ_a values, based on an approximation theory, an empirical formula was derived, as a function of frequency f, i.e., $\ell_a = \ell_a(f)$. This relationship is given based on an approximation theory and depicted in Fig. 4:

$$\ell_a = -4.6895 + \frac{46398.7}{f}.$$

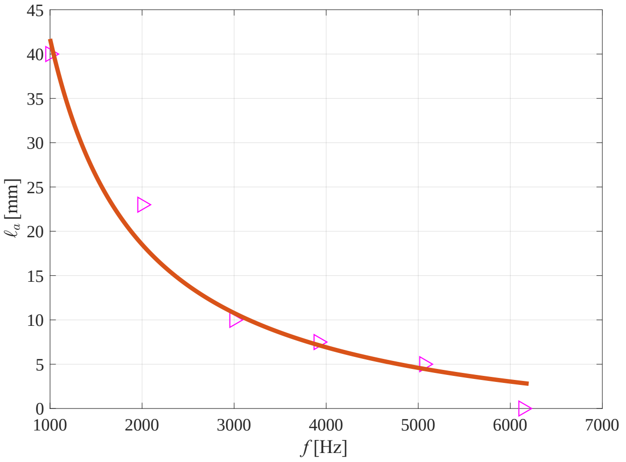

Fig. 4. Approximate value of ℓ_a as a function of frequency f.

3.2. *Influence of the horizontal inlet/outlet extensions on a single* D-EC

First, the influence of the length $\ell_{p,i}$ or $\ell_{p,o}$ or both of the horizontal extensions of the D-EC on the TL was analyzed. These considerations are similar to those published in (Selamet *et al.*, 2003; Łapka, 2007; Chaitanya, Munjal, 2011; Munjal, 2013; Xiang *et al.*, 2016; Chang *et al.*, 2019; Zhao, Li, 2022) but here they refer to the dedicated frequency.

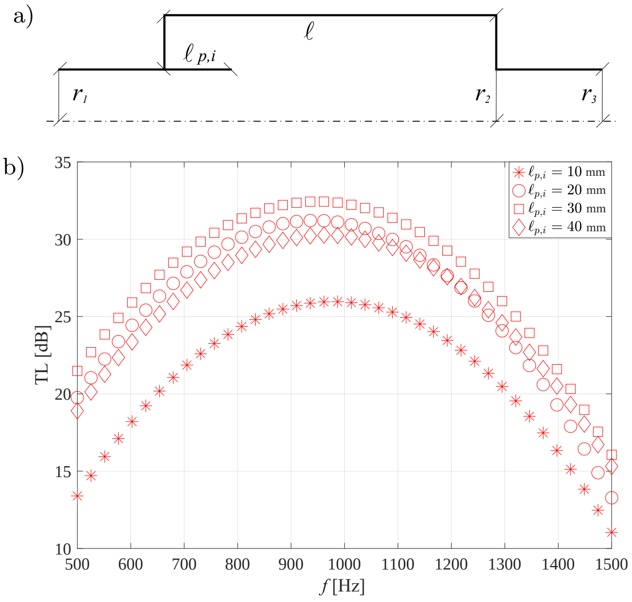

Fig. 5. Cross-section of the silencer with the horizontal inlet extension $\ell_{p,i}$ (a); effect of $\ell_{p,i} = \{10, 20, 30, 40\}$ mm on the TL, $f = 1000$ Hz (b).

At a frequency of 1000 Hz, the same horizontal extensions length $\ell_{p,i} = 30$ mm (first case) or $\ell_{p,o} = 30$ mm (second case) resulted in the same TL increase of about 9 dB; further increase in these lengths did not yield additional TL increase (Figs. 5 and 6). Whereas, using both horizontal extensions of the inlet and outlet lengths $\ell_{p,i} = \ell_{p,i} = 40$ mm (third case) produced a TL increase of about 21 dB (Fig. 7). However, if in the

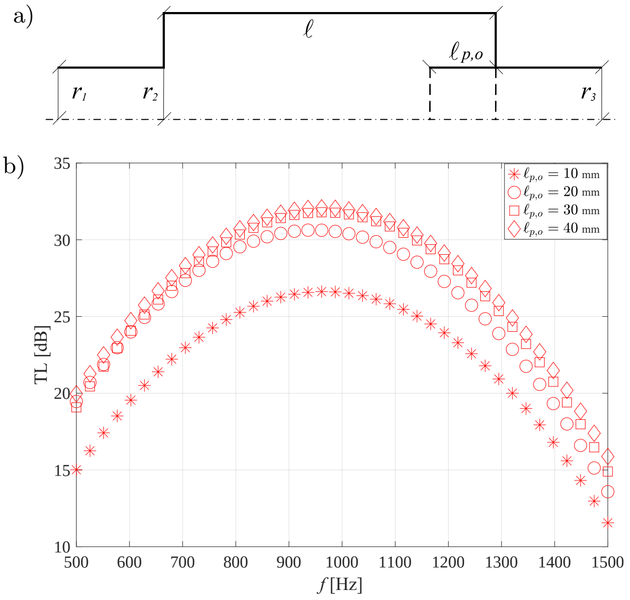

Fig. 6. Cross-section of the silencer with the horizontal outlet extension $\ell_{p,o}$ (a); effect of $\ell_{p,o} = \{10, 20, 30, 40\}$ mm on the TL, $f = 1000$ Hz (b).

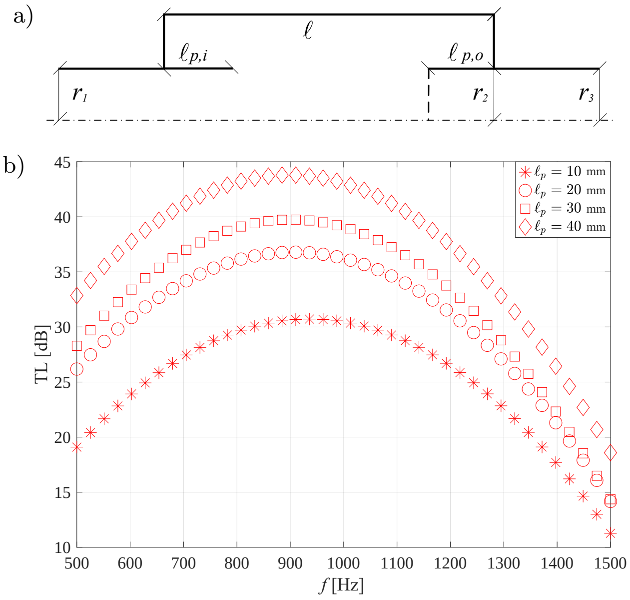

Fig. 7. Cross-section of the silencer with both horizontal inlet and outlet extensions $\ell_{p,i}$ and $\ell_{p,o}$ (a); effect of the $\ell_{p,i} = \ell_{p,o} = \ell_p = \{10, 20, 30, 40\}$ mm on the TL, $f = 1000$ Hz (b).

third case the sum of these lengths, i.e., $\ell_{p,i} + \ell_{p,o}$, is approximately equal to the length of $\ell_{p,i}$ (first case) or $\ell_{p,o}$ (second case), i.e., about 30 mm, then the TL increase is about 14 dB.

For frequency 3000 Hz the same horizontal extensions length $\ell_{p,i} = 30$ mm (Fig. 8) or $\ell_{p,o} = 30$ mm (Fig. 9) and for frequency 5000 Hz the same horizontal extensions length $\ell_{p,i} = 15$ mm (Fig. 11) or $\ell_{p,o} = 15$ mm (Fig. 12) gave the same maximum TL increase of about 9 dB. However extensions of the inlet and outlet by the same length $\ell_{p,i} = \ell_{p,o} = 15$ mm for 3000 Hz (Fig. 10) and $\ell_{p,i} = \ell_{p,o} = 5$ mm–10 mm for 5000 Hz (Fig. 13) gave the TL increase also of about 9 dB (cf. Chaitanya, Munjal, 2011).

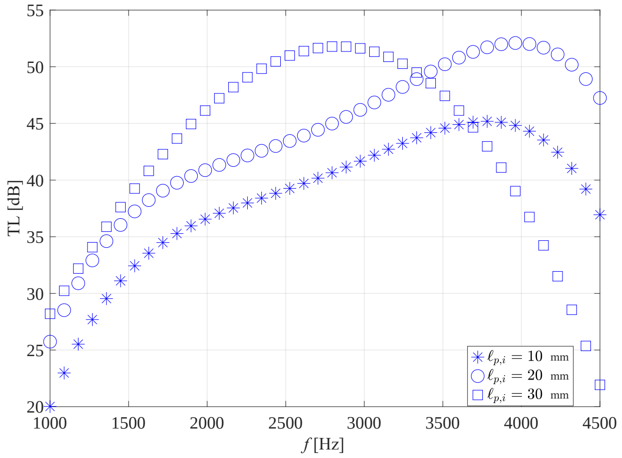

Fig. 8. Effect of $\ell_{p,i} = \{10, 20, 30\}$ mm on the TL, $f = 3000$ Hz.

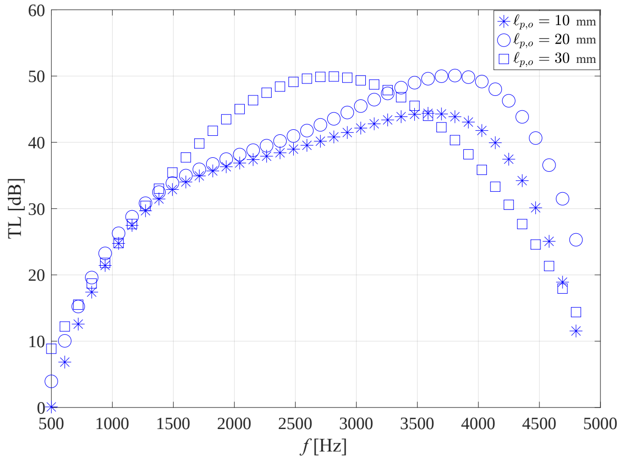

Fig. 9. Effect of $\ell_{p,o} = \{10, 20, 30\}$ mm on the TL, $f = 3000$ Hz.

3.3. Influence of the second D-EC

The simplest way to increase the TL of a silencer at the dedicated frequency is to connect two D-ECs in series. This is possible by inserting a transverse partition into the EC of the appropriate length, so that two D-ECs are formed. However, the geometric parameters of this partition also affect the TL value.

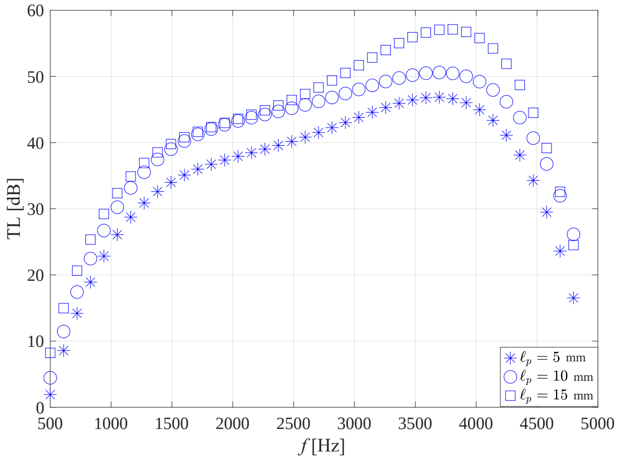

Fig. 10. Effect of $\ell_{p,i} = \ell_{p,o} = \ell_p = \{5, 10, 15\}$ mm on the TL, $f = 3000$ Hz.

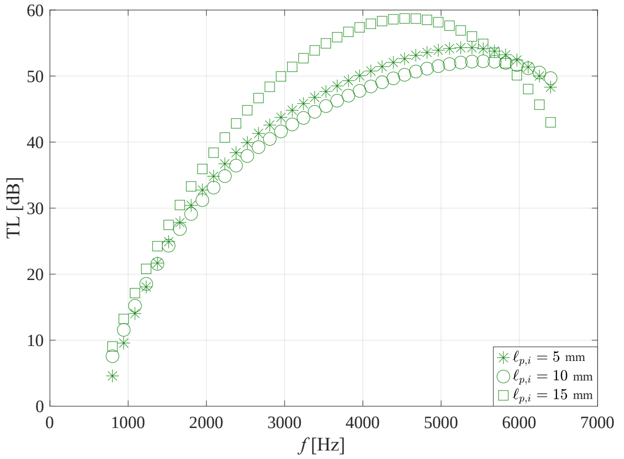

Fig. 11. Effect of $\ell_{p,i} = \{5, 10, 15\}$ mm on the TL, $f = 5000$ Hz.

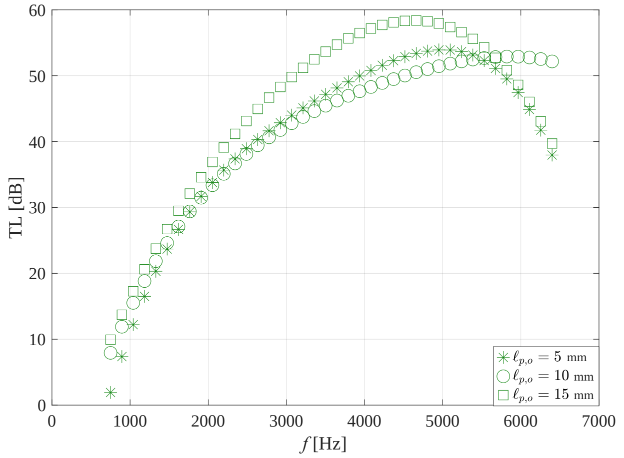

Fig. 12. Effect of $\ell_{p,o} = \{5, 10, 15\}$ mm on the TL, $f = 5000$ Hz.

First, for a selected baffle width of $h = 5$ mm and with the orifice diameter d_0 equal to the inlet and outlet diameters, i.e., $d_0 = 2r_1 = 2r_3 = 6$ mm, the TLs of a single D-EC and of two D-ECs were compared, Fig. 14.

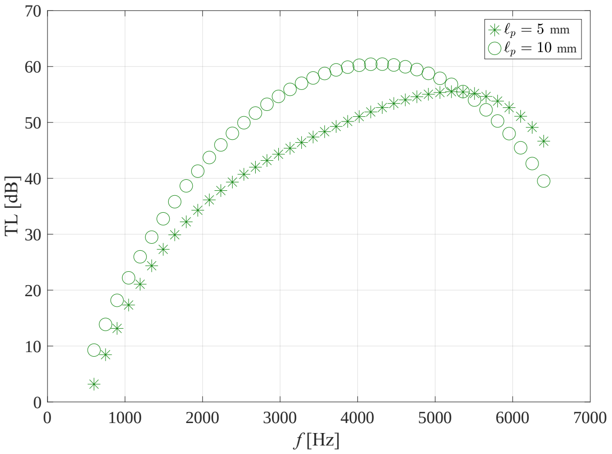

Fig. 13. Effect of $\ell_{p,i} = \ell_{p,o} = \ell_p = \{5, 10\}$ mm on the TL, f = 5000 Hz.

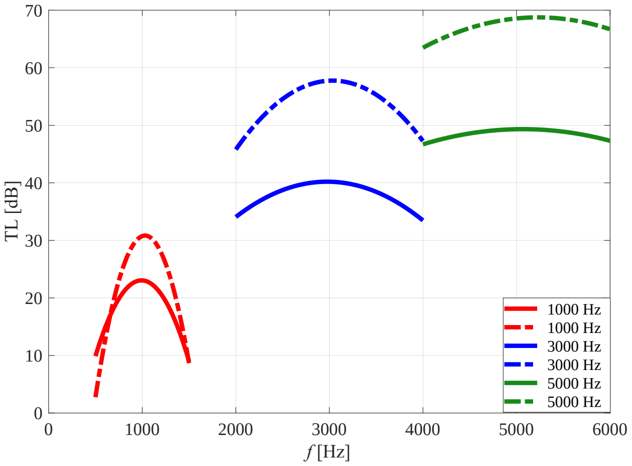

Fig. 14. Influence of the number of D-ECs on the TL at selected frequencies; solid lines – single D-ED, dashed lines – two D-EC.

It can be seen that an increase in the number of D-ECs from one to two causes an increase in the TL; this conclusion is qualitatively obvious. Furthermore, the double D-EC does not significantly shift the maximum TL, and it still functions as a dedicated silencer. Moreover, with an increase of dedicated frequency, the difference in maximum TL between one D-EC and double D-EC also increases, i.e., at 1000 Hz – the difference is about 7 dB, at 3000 Hz – about 17 dB, and at 5000 Hz – about 19 dB.

Next, the effect of the transverse partition width h between the D-ECs on the TL is analyzed. It is assumed that the partition orifice, as well as the inlet and outlet diameters, are the same as aforementioned; the results are depicted in Fig. 15.

As can be seen from Fig. 15, assuming a fixed transverse partition orifice diameter d_0, the transverse partition width h between the D-ECs influences the TL value at the dedicated frequency. In the analyzed frequencies, the optimal width h is about h = 10 mm, while a TL increase is about 7 dB–8 dB.

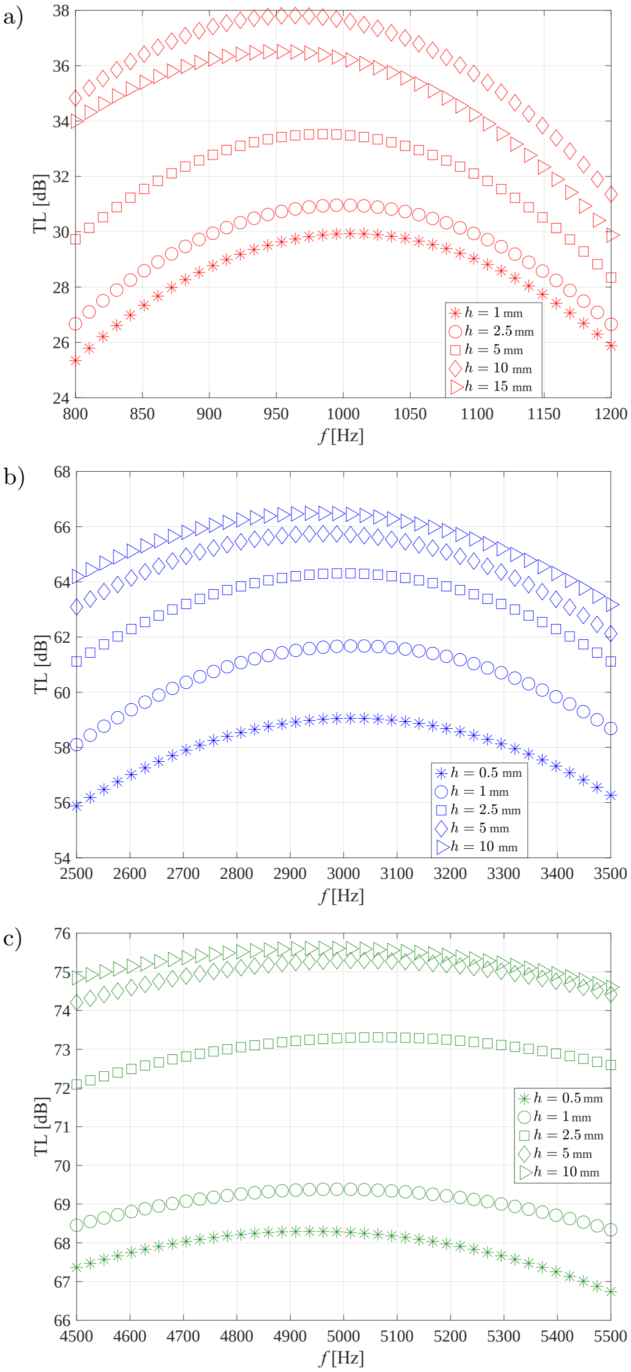

Fig. 15. Effect of the transverse partition width h [mm], d_0 = 6 mm, between D-ECs on the TL for selected frequencies: a) 1000 Hz, b) 3000 Hz, c) 5000 Hz.

Finally, the influence of the transverse partition orifice diameter d_0 between the D-ECs on the TL is analyzed. It is assumed that the partition orifice width is h = 5 mm, with the inlet and outlet diameters as aforementioned; the results are presented in the Fig. 16.

From Fig. 16, it follows that assuming a fixed transverse partition width h, the smallest orifice diameter d_0 of the transverse partition between the D-ECs provides the largest TL value at the dedicated frequency; here

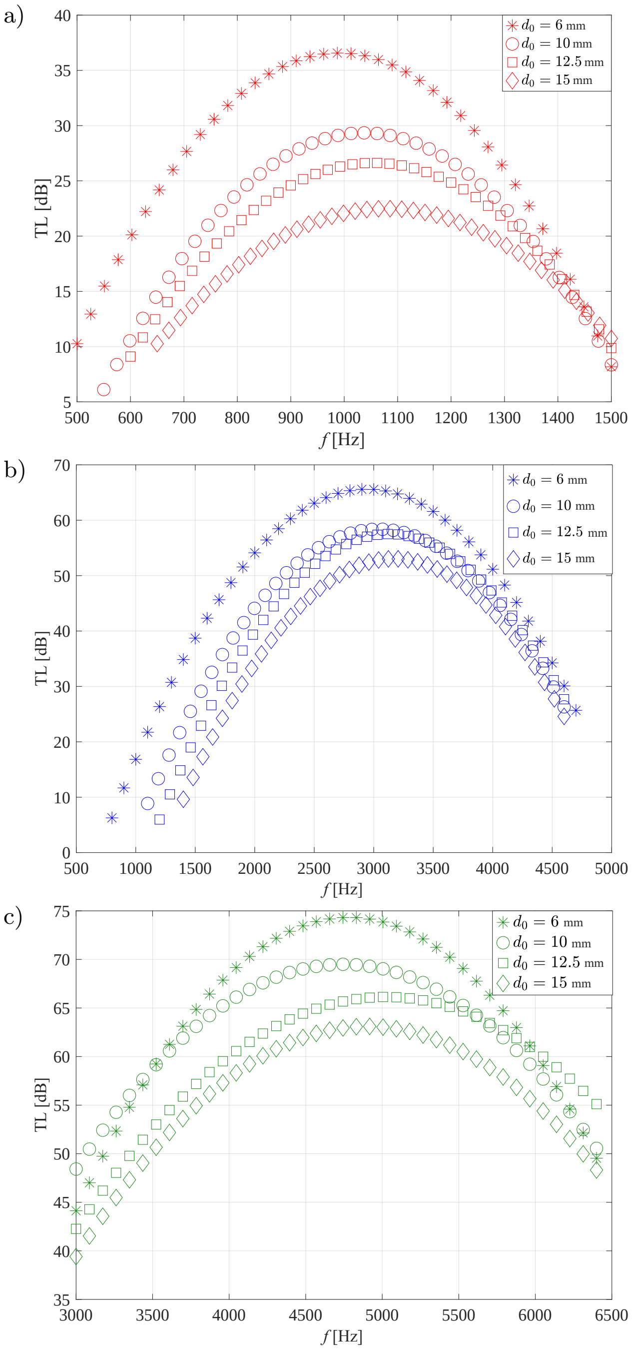

Fig. 16. Effect of the diameter of the transverse partition $d_0 = \{6, 10, 12.5, 15\}$ mm, $h = 5$ mm, between D-ECs on the TL for selected frequencies: a) 1000 Hz, b) 3000 Hz, c) 5000 Hz.

it is $d_0 = 6$ mm. However, the smallest diameter is dictated by technical operating conditions. By doubling the diameter d_0, e.g., from 6 mm to 12.5 mm, the TL value decreases by 10 dB–8 dB and the TL maximum slightly shifts towards higher frequencies.

4. Summary and general conclusions

It was shown that it is possible to build a simple silencer to damp noise at a dedicated frequency; it may even consist of a single EC. The effectiveness of such a silencer can also be easily increased, for example, by adding horizontal extensions to the inlet, the outlet, or both. Another simple method to improve noise reduction efficiency is to connect identical silencers in series. The most important conclusions from this study are as follows:

1) The plane wave theory gives a basis for determining the EC length for the dedicated frequency, and by adding an additional length, the D-EC is obtained. The D-EC is the simplest silencer for a dedicated frequency. The attached length was obtained from an empirical formula based on approximation theory for discrete experimentally obtained data.
2) For all analyzed frequencies, horizontal extension lengths, either $\ell_{p,i}$ or $\ell_{p,o}$, different for different frequencies, gave a TL increase of about 9 dB. A similar increase in TL was obtained for horizontal inlet and outlet extensions, provided that their combined length is the same as in the first and second case. Only at 1000 Hz, this increase is slightly greater.
3) Increasing the number of D-ECs obviously increases the TL. Moreover, as the dedicated frequency increases, the TL also increases.
4) For a fixed orifice diameter d_0 of the transverse partition between the D-ECs, there is an optimal width h that maximizes the TL value at the dedicated frequency.
5) For a fixed width h of the transverse partition between the D-ECs, the smallest orifice diameter d_0 provides the largest maximum TL value at the dedicated frequency. However, the smallest diameter d_0 is most often imposed due to technical reasons.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to this work, reviewed and approved the final manuscript.

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