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Experimental concept study of a small engine silencer unit based on microperforated elements

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Abstract. Considering the green transformation, more and more attention must be paid to reducing noise pollution, which is one of the most important environmental problems today. Internal combustion engine (ICE) powered hand tools and small appliances, such as leaf blowers, brush cutters, chainsaws, and lawn mowers, are examples of the most undesirable sources of noise in today's human environment. This paper discusses the acoustic properties of a novel and compact silencer for a small two-stroke ICE and proposes a novel concept with corresponding acoustic properties. The proposed solution has been measured on a test bench, and its properties, including transmission loss (TL) and reflection and absorption properties, have been experimentally determined. Using 3D printing technology and technological advantages, an innovative silencer with up to two microperforated (MP) panels, integrated into the expansion chamber of the original silencer, has been applied for rapid prototyping. As a result, noise reduction has been increased by at least 20 dB in the frequency range 800–4000 Hz.

Keywords: microperforated element, noise control, transmission loss, absorption coefficient.

1. INTRODUCTION

The quest for reducing noise pollution from internal combustion engine (ICE) exhaust systems has long been a focal point in various industries, including automotive, marine, and power generation. Noise control strategies play a vital role in enhancing user comfort, meeting regulatory standards, and minimizing environmental impact. Among these strategies, the utilization of efficient silencers stands out as a primary method to attenuate engine noise.

Silencers operate on two fundamental principles: dissipation and reflection. Dissipation involves the absorption of sound wave energy by resistive components, such as porous materials and perforated structures. This process is particularly effective at mid- to high frequencies, where sound energy can be effectively absorbed. On the other hand, reflection mechanisms work to reduce wave energy through multiple reflections from discontinuities and changes in the cross-sectional area. Reflection is especially beneficial at lower frequencies, where absorption may be less effective [1–3].

In recent years, microperforated (MP) panels have emerged as promising components for achieving sound dissipation in silencers [4–6]. These panels, characterized by numerous tiny perforations, offer enhanced acoustic performance while maintaining compactness and lightweight characteristics. Research conducted at Tallinn University of Technology (TalTech) has extensively investigated the application of microperforated panels in ICE exhaust silencers [7–9]. Studies have not only focused on their acoustic properties but also delved into issues such as endurance, reliability, and potential clogging phenomena in real-world operating conditions [10,11].

The current article builds upon this foundation by proposing a novel exhaust silencer design incorporating MP panels. Experimental acoustic characterization and optimization of various configurations are central to this

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endeavour. The selected MP panels, sourced from Sontech International AB under the Acustimet® brand [12], have undergone prior scrutiny by the authors, including assessments in multi-layered configurations to explore their full potential [8,9].

While significant attention has been devoted to large-scale engine silencers, relatively little research has targeted compact silencers for small engines. This research gap underscores the need to explore innovative approaches to enhance noise attenuation in constrained spaces while maintaining cost-effectiveness. Thus, the primary focus of the study is to investigate opportunities for improving the noise attenuation capabilities of small engine silencers. By addressing this gap, the article aims to contribute valuable insights into the realm of noise control strategies, particularly concerning ICE exhaust systems, and pave the way for more efficient and quieter engine designs in various applications.

2. EXPERIMENTAL STUDIES

The experimental studies were carried out in the acoustic laboratory of TalTech. The key acoustic parameters of the silencers were determined by using dedicated one-port and two-port test stands, including reflection and absorption coefficients, transmission loss (TL) parameters, and sound pressure levels (SPL).

2.1. The reflection and absorption coefficient

The reflection and absorption coefficients are important parameters in the characterization of noise attenuation performance, the determination of which is discussed below.

The widely used method to determine the absorption coefficient of materials is the transfer function method using an impedance tube test stand, following ISO 10534-2:1998 (see Fig. 1) [13].

The silencer is fitted into the rigidly closed end of the tube and the outlet of the silencer is sealed to achieve a closed system. By applying excitation noise (white noise) from the electro-dynamic driver located in the end of the tube (see Figs 2 and 3) and by measuring the acoustic signals from two microphones, it is possible to calculate the reflection and absorption coefficient of the silencer tested. The plane wave acoustic pressures at the two microphones separated by distance s can be expressed as [14]:

$$p_1(f) = p_{1+}(f) + p_{1-}(f) \text{ and}$$

$$p_2(f) = p_{1+}(f) exp(-ik_+ s) + p_{1-}(f) exp(ik_- s),$$

where p is the acoustic pressure, f is the frequency, $k = 2\pi f/c$ is the wave number, c is the speed of sound, – and + denote the pressure waves propagating in the negative and positive direction along the tube axis. The reflection coefficient at microphone 1 is defined as [14]:

$$R(f) = p_{1-}(f)/p_{1+}(f).$$

It can be shown that

$$R(f) = \left(H_{12}^e - exp(-ik_+ s)\right)/(exp(ik_- s) - H_{12}^e),$$

where $H_{12} = p_2/p_1$ is the transfer function between the inductively mounted measurement microphones 1 and 2.

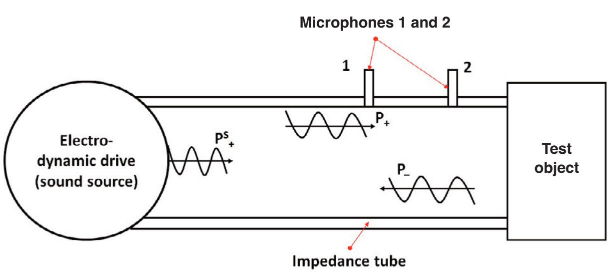

Fig. 1. One-port measurement set-up for the experimental determination of the absorption coefficient, where 1 and 2 denote locations of the microphones.

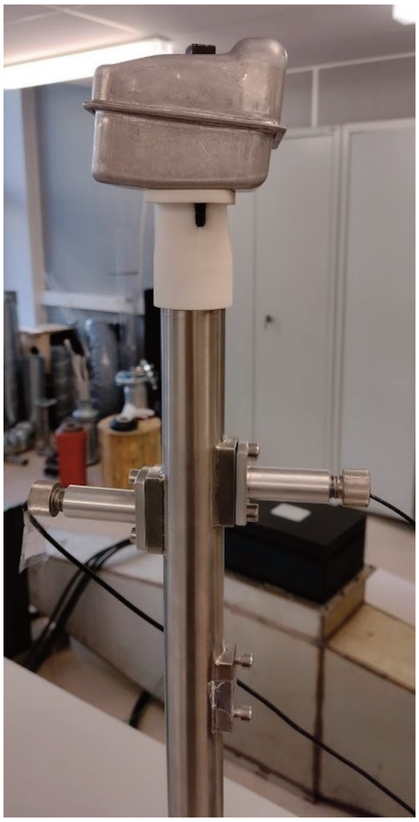

Fig. 2. One-port test stand (impedance tube) with standard silencer unit installed (SREF) with silencer output duct sealed.

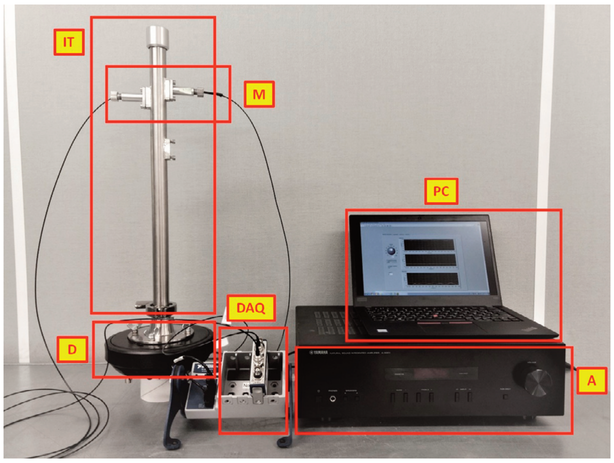

Fig. 3. One-port (impedance tube) test rig configuration: IT – impedance tube (inner diameter 28 mm), M – two 1/4” microphones, D – electro-dynamic driver (sound source), DAQ – data acquisition system, PC – computer, A – excitation signal amplifier.

Then the absorption coefficient of the silencer is calculated as [14]:

$$\propto_s (f) = 1 - |R(f)|^2.$$

According to the impedance tube diameter of 28 mm, the upper measurement limit or cut-off frequency is 8376 Hz, and the lower limit, which is determined by the microphone separation (s = 16 mm), is 200 Hz. Therefore, the observation range is chosen from 200–4000 Hz, where the upper limit is chosen two times lower due to the practical working range of the silencer. In such an experiment, the investigated silencer is placed onto the tube with varying configurations, which are described in Section 2.4.

Experimental tests were carried out using the following equipment (see Fig. 3):

- two 1/4” prepolarized pressure microphones (G.R.A.S. 40BD),
- four channel DAQ analyser (NI 9234) and USB carrier (NI USB-9162),
- electro-dynamic driver (BMS 4591),
- excitation signal amplifier (Yamaha AS201).

2.2. Transmission loss measurements

To determine the noise reduction performance of the MP panels set-up in a variety of silencer layouts, TL was measured by using a dedicated two-port test facility.

The TL measurement is based on the two-port method [15], where two electro-dynamic drivers are used as excitation sources and the relevant data are measured by four microphones (see Fig. 4). The measurement frequency range in this method is limited to 200–8376 Hz. The lower frequency is determined by the acoustic driver frequency limit; the upper frequency is limited by the cut-off frequency of the duct and by the microphone separations $s1$ and $s2$ (16 mm). This frequency, in the case of circular cross-sections, is given by $fcut - on = 1.84c\,(1 - M2)\,/\,(d\pi)$.

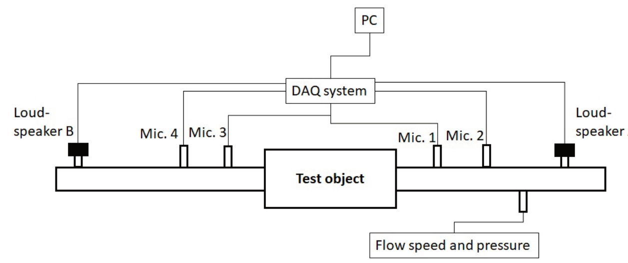

Fig. 4. Two-port measurement set-up for the determination of acoustic transmission loss.

The experiment set-up is presented in Fig. 5, where the test object (expansion chamber) and relevant instruments can be viewed.

The well-known two-microphone approach was used to obtain complex pressure amplitudes of the travelling acoustic waves at the inlet and outlet cross-sections of the test-section. The method is based on the transfer matrix representation of the two-port, and in frequency domain the relationship between the acoustic states at the A (upstream) and B (downstream) (see Fig. 5) sections can be written as [16,17]:

$$\begin{bmatrix} p_{A-} \\ p_{B+} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} p_{A+} \\ p_{B-} \end{bmatrix},$$

where p denotes the complex plane wave acoustic pressure at the A and B sides of the acoustic two-port and S is the scattering matrix, representing the silencer. To find the

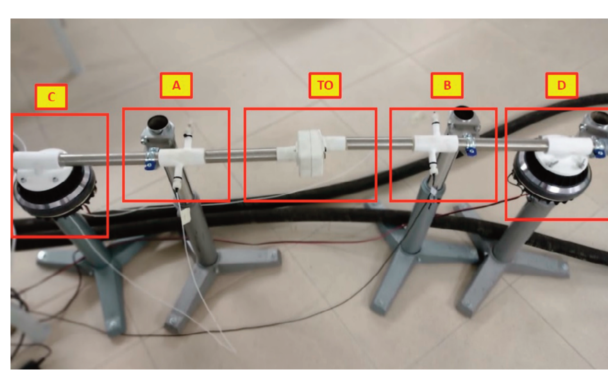

Fig. 5. Two-port test stand with simple expansion chamber silencer S01 installed (in the middle): A – microphones 1 and 2 (side A), B – microphones 1 and 2 (side B), C – electro-dynamic driver (sound source) (side A), D – electro-dynamic driver (side B), TO – test object.

four elements of S from two equations, two independent test states must be created. The method used here to create the independent test states was the two-source method, which is less sensitive to random errors than the two-load method [17]. The first test state was obtained by activating the acoustic driver at the A side and the second state by turning on the acoustic driver at the B side while turning off the acoustic driver at the A side. The two-port matrix for the silencer was then calculated from the following relationship:

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} p_{A-,1} & p_{A-,2} \\ p_{B+,1} & p_{B+,2} \end{bmatrix} \cdot \begin{bmatrix} p_{A+,1} & p_{A+,2} \\ p_{B-,1} & p_{B-,2} \end{bmatrix}^{-1},$$

where the indices 1 and 2 indicate the test state. By using the two-microphone approach to perform the wave decomposition in the inlet and outlet measurement sections, the travelling pressure data can be computed. By using the determined two-port data, TL is calculated by the following expression [16,17]:

$$TL = 10 \log_{10} \left(\frac{1}{|S_{21}|^2} \right),$$

where S_{21} is the S-matrix element describing sound transmission through the test object [17].

The transmission loss experiments were performed by using the following equipment:

- four 1/4” prepolarized pressure microphones (G.R.A.S. 40BD),
- two four channel DAQ analysers (NI 9234),
- USB chassis (NI USB-9162),
- two electro-dynamic drivers (BMS 4591),
- signal amplifier (Yamaha AS201),
- axial blower (Kongskilde 300TRV),
- flow speed meter,
- pressure meter.

2.3. Sound pressure level

SPL measurements play a critical role in various fields. SPL refers to the intensity of sound waves expressed in decibels (dB), providing valuable insights into the loudness or volume of a sound. Accurate SPL measurements are essential for assessing noise pollution levels, ensuring compliance with regulatory standards, optimizing acoustic design, and safeguarding human health and well-being.

To conduct precise SPL measurements, specialized equipment and methodologies were employed. The test silencer was fitted to the chainsaw which stayed on the stand above the ground (around 0.8 metres). Measuring equipment, the sound level meter TES 52, was placed on the same level as the outlet of the silencer, with a distance of one metre (see Fig. 6). Several measurement points were selected (eight positions), evenly spread clockwise with the measuring range set to C-scale SLOW in all the cases.

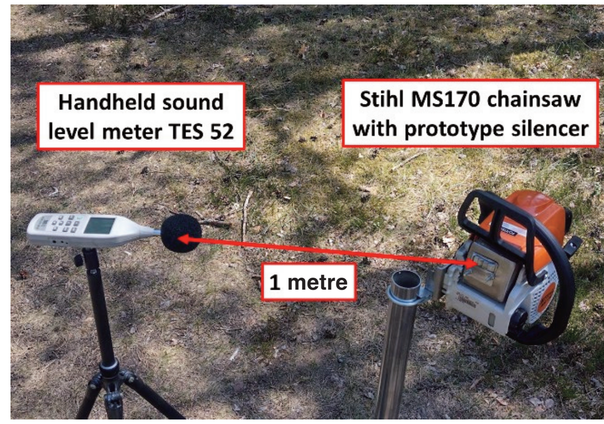

Fig. 6. SPL measurement set-up in free-field conditions.

For the SPL measurements, the reference silencer (SREF in Fig. 2) and the best prototype silencer (S04) were compared in full speed mode of the chainsaw, and the results are presented below.

2.4. Test object

To experimentally investigate different configurations of the silencer, MP panels were added in different positions (see Fig. 7). The simplest configuration designated as S01 is a simple expansion chamber such as the standard

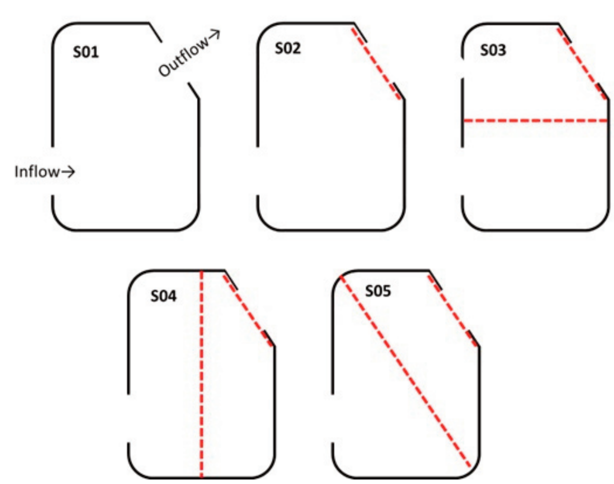

Fig. 7. Different silencer configurations tested with an added MP panel (red dashed line): S01 – simple expansion chamber, S02 – added MP panel at outlet, S03 – added MP panel in horizontal direction, S04 – added MP panel in vertical direction, S05 – added MP panel in diagonal direction.

reference silencer unit, which acts as a reactive silencer. In other configuration cases S02 to S05, MP panels were added, which also increased resistivity of the silencer. The horizontally, vertically, and diagonally placed MP panel divides the silencer volume into two discrete chambers.

One benefit from these designs is that the standing waves in these chambers occur at higher frequencies, and the attenuation at lower frequencies increases. For the cases S02–S05, the mean gas flow crosses the panels. Thus, the resistive performance of the panels is increased with the cost of pressure drop increase. In this respect, the case S05 is more favourable due to the increased MP panel surface area.

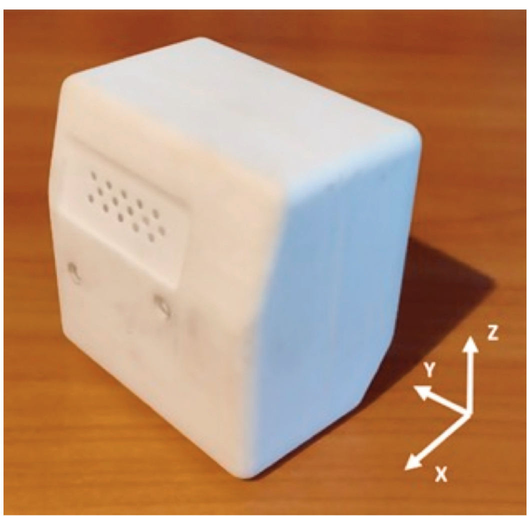

Fig. 8. Test object for experimental studies: 3D printed simple expansion chamber (S01).

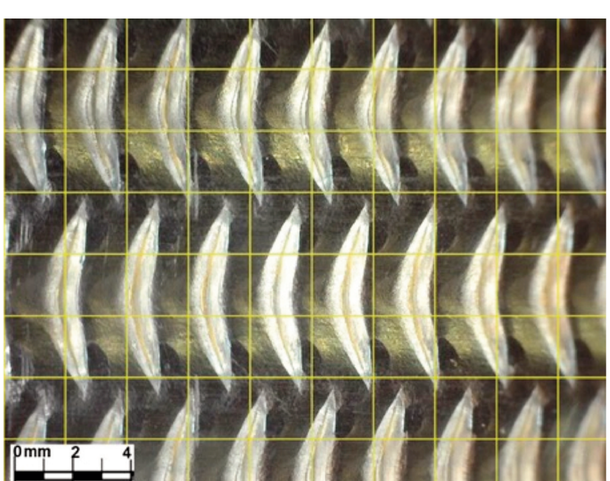

Fig. 9. Commercially available MP panel slit-shape perforation under 8x magnification with 4% porosity.

To investigate different silencer configurations with incorporated MP panels, selective laser melting (SLM) technology was implemented to manufacture a prototype silencer unit made from plastic and stainless steel. Considering the design constraints of the silencer in terms of space availability, the prototype has similar size as the standard silencer unit, although with slightly bigger dimensions (inner dimensions X = 53 mm, Y = 78 mm, Z = 77 mm), but can still be fitted on the chainsaw.

3. RESULTS

The results of the experimental investigations are presented and discussed in this section. First, the absorption coefficients were measured and expressed as a function of the sound frequency for the different silencer configurations S01, S02, S03, S04, S05.

In Fig. 10, the comparison of absorption coefficients for the standard silencer SREF and simple expansion chamber S01 are presented. Generally, both silencers behave quite similarly, only absorption maxima peaks have been shifted slightly due to the dimensional differences. Absorption of the standard silencer increases over frequencies 2500 Hz due to the installed wire mesh and flame guide at the output orifice, which acts as a perforated panel at the outlet.

In Fig. 11, the absorption coefficients for silencer configurations S02 to S05 with added MP panels are presented. Configuration S02, with an added MP panel at the output only, has similar reflection and absorption characteristics as S01; however, the first absorption peak at 180 Hz has shifted slightly to a lower frequency and dropped to 0.8. At higher frequencies of around 3700 Hz, a small improvement of absorption properties can be seen. Configurations S03 to S05 have additional microperforated panels across the volume, keeping the microperforated sheet at the output. With added panels, the absorp-

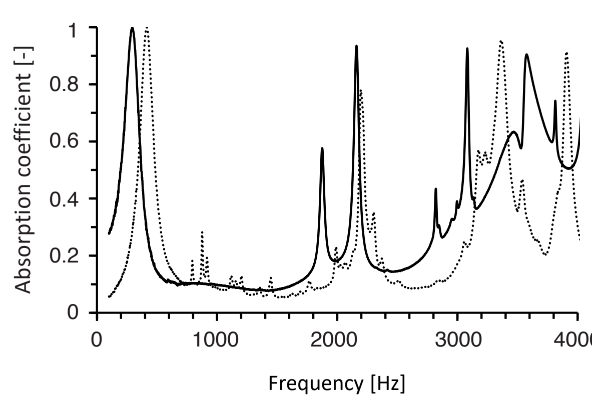

Fig. 10. Absorption coefficients for reference silencer SREF (solid line) and simple expansion chamber silencer S01 (dotted line).

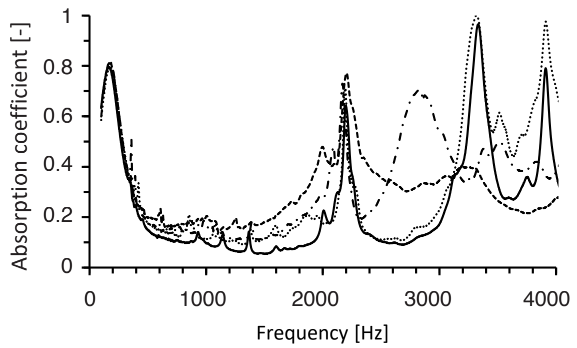

Fig. 11. Absorption coefficients for silencer configuration S02 (solid line), S03 (dotted line), S04 (dashed line), and S05 (dash-dot line).

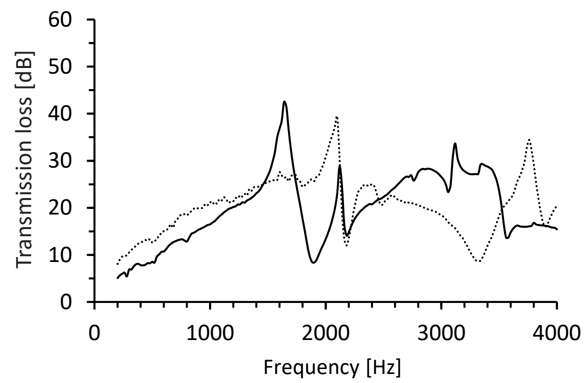

Fig. 12. TL measurements without the presence of mean flow: standard silencer SREF (solid line) and simple expansion chamber silencer S01 (dotted line).

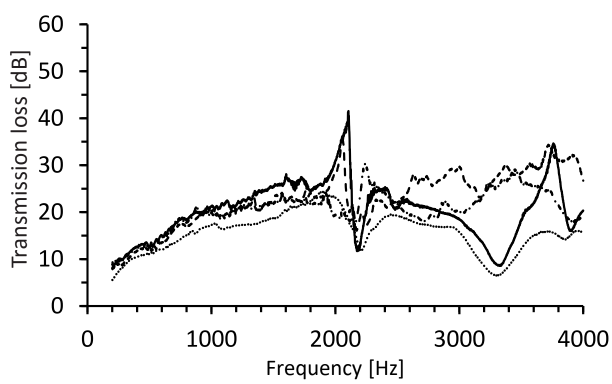

Fig. 13. TL measurements without the presence of mean flow: silencer S02 (solid line), S03 (dotted line), S04 (dashed line), and S05 (dash-dot line).

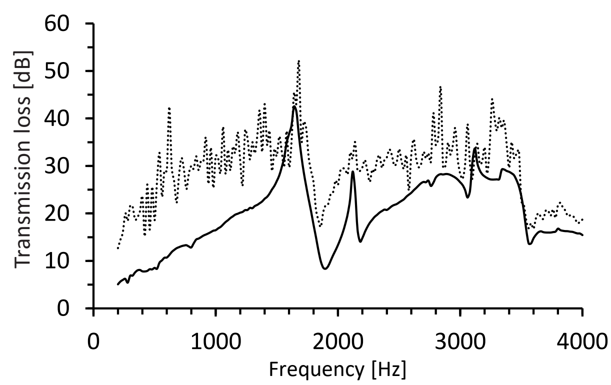

Fig. 14. TL measurements with and without the presence of mean flow (flow speed expressed as the Mach number). Standard silencer SREF: M = 0.00 (solid line) and M = 0.04 (dotted line).

tion properties in the frequency range of 500–4000 Hz are improved. The configurations with vertically placed (S04) and diagonally placed (S05) microperforated sheets are the best cases, being better across almost the entire frequency range.

TL was measured at the two-port test stand with and without the presence of mean flow. Initially, measurements were conducted without the mean flow conditions for the standard silencer unit SREF and different silencer configurations S01 to S05 (see Figs 12 and 13).

Comparing the standard silencer and simple expansion chamber (see Fig. 12), we can observe that at lower frequencies up to 1600 Hz, the S01 configuration has better performance over the standard silencer (up to 5 dB), which is explained with S01 having slightly larger volume and, therefore, increased reactive attenuation capability. Measurements of TL for the configurations S02 to S05 are presented and compared in Fig. 13, which proves that S04 performs very well over all the frequency range. The decrease at frequencies 1500–2200 Hz can be explained by efficiency loss on the MP panel at the outlet due to decreased flow caused by the vertically placed MP panel.

TL measured in the presence of mean flow is shown in Figs 14 and 15. For the test cases SREF and S01, the major differences occur in the presence of mean flow only in the first case. In the simple silencer configuration S01, there are none or very few dissipative properties; therefore, mean flow does not affect TL characteristics too much. The only significant improvement of TL is in the frequency range of 2500–3800 Hz.

Subsequently, based on the measurements without the presence of mean flow, the configurations S02 and S03 were omitted from further measurements, and only the configurations S04 and S05 were measured in the presence of mean flow (see Figs 16 and 17). For both S04 and S05, TL is increased with the presence of mean flow; however, the mean flow speed does not have any influence on

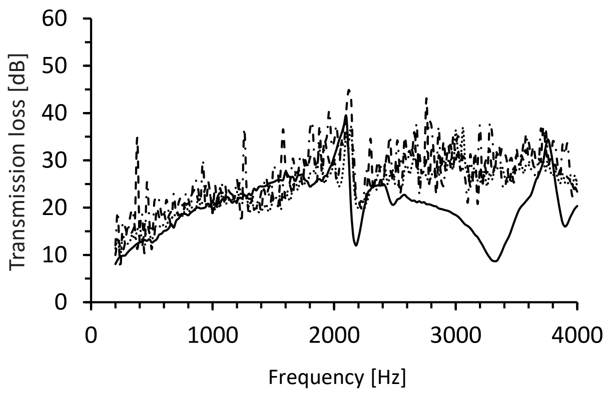

Fig. 15. TL measurements with and without the presence of mean flow (flow speed expressed as the Mach number). Simple expansion chamber silencer S01: M = 0.00 (solid line), M = 0.03 (dotted line), M = 0.05 (dashed line), and M = 0.06 (dash-dot line).

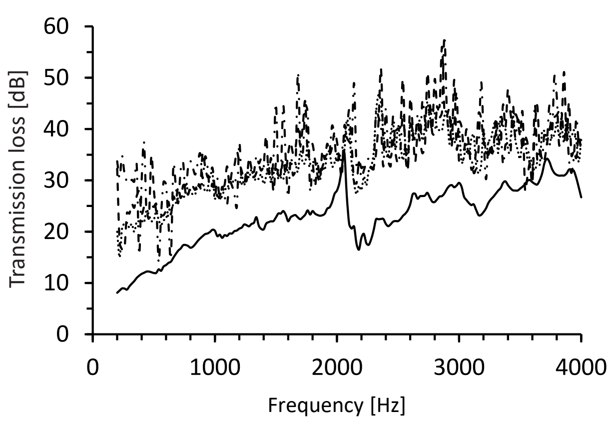

Fig. 16. TL measurements with and without the presence of mean flow (flow speed expressed as the Mach number). Silencer S04: M = 0.00 (solid line), M = 0.04 (dotted line), M = 0.05 (dashed line), and M = 0.07 (dash-dot line).

the TL values. It appears that the configuration S04 compared to S05 has at least 30–35 dB better TL over the entire frequency range.

The results of the SPL measurements are presented in Fig. 18, where we can observe lower noise emittance from the silencer configuration S04 at full speed (wide open throttle) conditions. At almost every measurement point, the noise level is reduced at least up to 1.5–2 dB.

Finally, the measurements of pressure drop due to mean gas flow were conducted for all silencer configurations and are presented in Fig. 19. It is clear from the results that the most restrictive is the standard silencer SREF and the least restrictive is the simple expansion chamber S01. Since S04 and S05 include the integrated

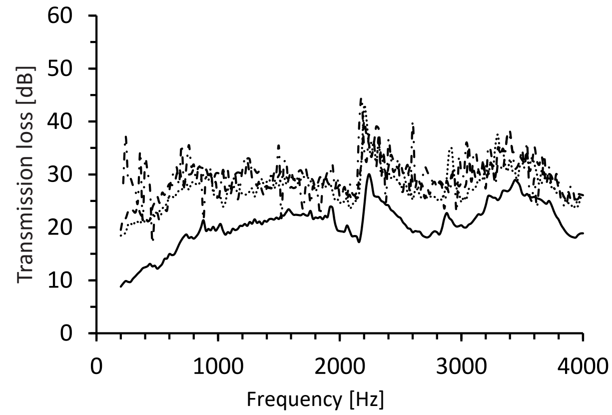

Fig. 17. TL measurements with and without the presence of mean flow (flow speed expressed as the Mach number). Silencer S05: M = 0.00 (solid line), M = 0.02 (dotted line), M = 0.04 (dashed line), and M = 0.06 (dash-dot line).

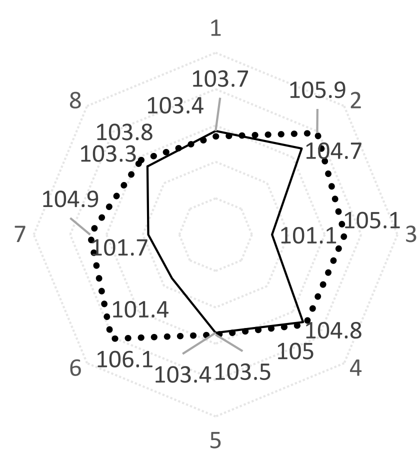

Fig. 18. SPL measurements for standard reference silencer SREF (dotted line) and silencer configuration S04 (solid line).

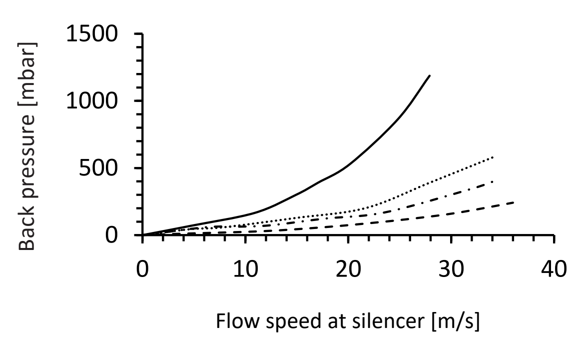

Fig. 19. Back pressure measurement for standard silencer configurations SREF (solid line), S01 (dashed line), S04 (dotted line), and S05 (dash-dot line).

MP panels, the increase in flow restriction is as expected, but this is still lower than in the standard SREF unit.

4. CONCLUSIONS

Acoustic properties of different test silencer configurations, including the standard silencer unit, are experimentally studied in this paper. The results include the absorption characteristics measured on the one-port test stand and the transmission loss measured on the two-port test stand. Due to space limitation in the silencer, the reflective properties cannot be improved; therefore, the resistive properties had to be increased. The results prove the microperforated panels' suitability and efficiency for implementations in a limited space environment, while offering reduction in the pressure drop levels. The MP panel placed across the silencer exhibits good potential for noise attenuation in the frequency range of 200–4000 Hz, while also representing a simple and economical solution for mass production.

Further studies should include 1D and/or 3D simulation to verify experimentally measured results with the analysis of measured impedance properties in different silencer configurations as well as to measure the source spectrum for the targeted silencer design.

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Mikroperforeeritud elementidel põhinev jätkusuutliku müra vähendamise kontseptsiooniuuring

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Mürasaaste on tänapäeval üks suuremaid keskkonnaprobleeme. Sisepõlemismootoriga käsitööriistad ja väikeseadmed, nagu lehepuhurid, võsalõikurid, kettsaed ja muruniidukid, on näited kõige ebasoovitavamatest müraallikatest. Artiklis käsitletakse väikese kahetaktilise sisepõlemismootori jaoks mõeldud uue kompaktse summuti akustilisi omadusi käsitööriistade rakendustes. Pakutakse välja uudne summuti kontseptsioon koos vastavate akustiliste omadustega, sealhulgas ülekandekadu ning peegeldus- ja neeldumisomadused, mis on katsestendil katseliselt määratud. Summuti kiireks prototüüpimiseks rakendati 3D-printimise tehnoloogiat kuni kahe mikroperforeeritud paneeliga, mis integreeriti summuti paisumiskambrisse. Selle tulemusena on mürasummutust suurendatud vähemalt 20 dB sagedusvahemikus 800–4000 Hz.