Noise silencer design using triply periodic minimal surfaces

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Abstract: *Noise reduction is a problem of great global interest, as we are surrounded by machines that produce noise emissions in one way or another. The 20th century saw the start of a strong development in noise reduction methods, with different methods being developed over the years, but the greatest advances in their application have been seen in recent decades. The proposed solution aims to solve the limitations of classic noise attenuators by combining two effects, destructive interference and Helmholtz resonator, and introducing a slightly atypical geometry compared to classic designs. The proposed geometry was mathematically defined a long time ago, but in recent years it has become of great interest in various fields, from CO2 capture to heat exchangers.*

Key Words: *acoustics, sound attenuation, muffler, triply periodic minimal surface, transfer matrix method*

NOMENCLATURE

A, B, C, D – matrix components
L - section length
S – area
T – transfer matrix
TL - transmission loss
c – speed of sound
k – wavenumber
p - sound pressure
u – particle velocity
ρ - fluid density
$[\ ]_1, [\ ]_2, \ldots, [\ ]_i$ - related to the section number

1. INTRODUCTION

It is well known that prolonged exposure to loud noises can irreparably affect hearing. For this reason, it is common practiced to use noise attenuation devices both for common applications (mainly vehicles) and for machines that work with various fluids [1]. Attenuation of sound is done/ Sound can be attenuated by two methods: absorptive or reactive attenuation. Absorptive attenuation consists of converting acoustic radiation into heat by a sound absorbing material. In reactive attenuation, sound waves are reflected back towards the noise source. Applications in various fields have demonstrated that it is possible to integrate solutions that use both methods of noise reduction [2]. Internal combustion engines are one of the main sources of noise pollution today. The pressure disturbances that come from the evacuation of this type of motors are attenuated in the muffler, this introduced element being considered an acoustic soundproofing device. The evacuation process consists of releasing a pulsating flow of exhaust gases into the environment. Pressure waves, which cross the flow domain at the speed of sound relative to the exhaust gas, escape with a high velocity producing an offensive exhaust noise. Depending on the operating of the engine, the overall sound pressure level may be lower or higher [2]. In internal combustion engines there are two main sources of noise: the vibration of the engine components (intake, crankcase, cylinder head), which give the components with high frequencies and the flow of flue gases through the exhaust manifold and the corresponding piping (with variations of sections), which give low frequencies [3]. In addition to the high attenuation efficiency of the acoustic radiation, it must be taken into account that the backpressure generated in the system must be minimized [4].

Noise attenuation is not only achieved by evacuating internal combustion engines. An interesting solution is proposed in [5], where a noise attenuator is placed at the entrance to the compressor in the supercharger group. Speaking of air routes, the solution of noise attenuators is also present in air conditioning installations both in terrestrial applications (offices) [6] and in aeronautical applications (passenger cabin) [7], as well as in the attenuation of noise produced by weapons [8]. Industrial processes and machinery are the leading cause of different types of pollution. One of most recent concerns is noise pollution, which is getting more and more attention due to the fact that at least 15% of industrial workers are exposed to noise levels over 85dB, fact that leads to hearing loss and other hearing damage [9].

Although in the industrial sectors noise sources are varied and complex, they can be divided in sounds that propagate through air, through solids or are a result of diffraction and/or reflection on different surfaces. Addressing sound pollution is a complex task and to do so, it is needed to customize different noise reduction methods in order to meet the specific requirements of the targeted goal. Recent advances in noise reduction have involved the use of different combinations of specific devices and their adaptation to the needs of each particular case. In summary, noise is a common factor that affects people's general health and reduces their comfort. Noise generated by domestic appliances has been shown to disrupt sleep, reduce people’s capacity to concentrate and work, and is a stress factor [10].

2. CONSTRUCTIVE SOLUTIONS

Depending on how the noise from the aforementioned installations is attenuated, several constructive solutions can be identified: Baffle Muffler, Resonance Muffler, Wave cancellation muffler, Absorptive Muffler, Combination Muffler. A baffle muffler represents a muffler which uses a mechanical device, usually a baffle, which is used to disrupt sound waves. Different designs of mufflers containing baffles, ranging from simple designs of exhausts pipes, to different combinations and geometries, like the ones proposed by S. Kamarkhani et al. [12], which can provide transmission losses of up to 91dB. They can be integrated in the version with tunable resonators [13]. Resonances can form/occur in the exhaust and tail pipes as well as in the muffler [11], the interacting waves being shown in Figure 1.

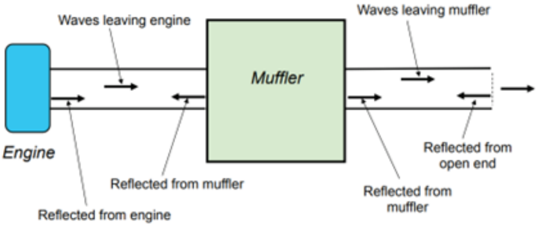


Fig. 1 Representation of waves interference within the flow path of gases coming from an IC engine [11]

A resonance muffler combines the perks of a resonator, which is designed to change the sound emitted by a source, with those of a muffler. This results in a change in both frequency and sound level. A classical geometry, with several chambers, is presented in Figure 2. In this way, the reflected sound wave and the incident sound wave cancel each other out. The resulting sound has a lower frequency, and recent advances in this domain use an active wave generator, that creates an opposite wave to the incoming one so that this phenomenon happens.

Sound attenuation in absorptive mufflers devices is done by using different materials that absorb sounds of different frequencies. The materials used range from fiber glass, wool, porous or high density materials, the decision being based on sound frequency and level. The different geometries of some of the materials used, as well as their microscopic structure are presented in [15].

Combination mufflers are created by combining some of the above-mentioned solutions (as shown in Figure 3), to overcome design complications or to meet operational requirements where necessary. This combination provides good attenuation of noise and works well over a large spectrum of frequencies.

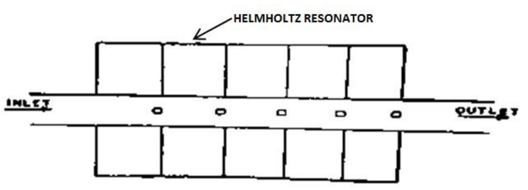


Fig. 2 Resonance muffler [14]

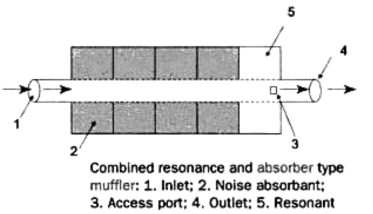


Fig. 3 Combination muffler [14]

The most recent advances in noise reduction involve using these types of combination mufflers. The remaining technical solutions have either reached a maturity and design level that is hard to surpass, or have reached their full potential in terms of materials used and operating parameters. Combining different types of noise-attenuating devices can provide a more precise approach when talking about customization for different projects, as they can be combined and designed to meet specific needs. For example, there are many types of combined mufflers designs, meant for different purposes, like the one presented by Wu et al [16], which modeled and conducted experiments on a hybrid resonator muffler which combines the benefits of Helmholtz theory and quarter wavelength tube to attenuate a larger spectrum of noise. A similar design is presented in [4].

3. ANALYTICAL CALCULATION MODELS

Each classic baffle muffler can be approximated with a series of sectors or elements that can be represented by a transfer matrix. The matrix writing for an acoustic component of any shape can be done as shown in Figure 4.

These transfer matrices can be subsequently combined so that the performance of the entire system can be estimated [17]. The transfer matrix for the analysed sectors [11] in the calculation can be written in the form of equations (1) - (3)

$$[\boldsymbol{T_i}] = \begin{bmatrix} \boldsymbol{A_i} & \boldsymbol{B_i} \\ \boldsymbol{C_i} & \boldsymbol{D_i} \end{bmatrix}_{\boldsymbol{2x2}} \tag{1}$$

$$\begin{Bmatrix} p_1 \\ S_1 u_1 \end{Bmatrix} = [\boldsymbol{T_1}][\boldsymbol{T_2}][\boldsymbol{T_3}] \dots [\boldsymbol{T_n}] \begin{Bmatrix} p_2 \\ S_2 u_2 \end{Bmatrix} = [\boldsymbol{T_{system}}] \begin{Bmatrix} p_2 \\ S_2 u_2 \end{Bmatrix} \tag{2}$$

$$[T_{system}] = \begin{bmatrix} A_{system} & B_{system} \\ C_{system} & D_{system} \end{bmatrix}_{2x2} \tag{3}$$

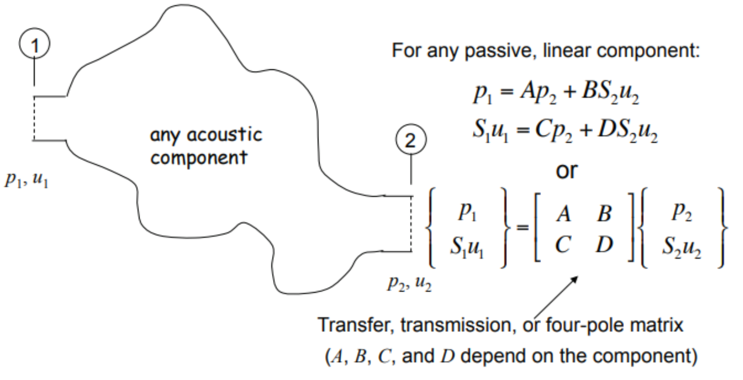


Fig. 4 General calculation model [11]

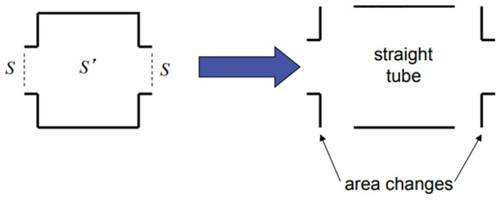


Fig. 5 The simplest geometry for a muffler [11]

For a sector in which the transition is made from one section to another (according to Figure 5), relation (4) for the transfer matrix can be written.

$$[T] = \begin{bmatrix} \cos(kL) & \frac{j\rho_0 c}{S'}\sin(kL) \\ \frac{jS'}{\rho_0 c}\sin(kL) & \cos(kL) \end{bmatrix} \tag{4}$$

The matrix writing can be transformed into an explicit equation [18] of the form of relation (5). Other variants with several expansion chambers communicating with each other in different ways, are theoretically presented by both Vasile [17] and Datchanamourty [19].

$$TL_1 = 20lg\left\{\frac{1}{2}\left|\cos(kL) + j\frac{S_1}{S}\sin(kL) + j\frac{S}{S_1}\sin(kL) + \cos(kL)\right|\right\} \tag{5}$$

In the real case, it must be taken into account that there is a lateral propagation at 90 degrees, asymmetric in the wall area, the flow channel having the shape in the horizontal plane according to Figure 6, where the lengths l_1 and l_2 are equal. The mathematical description of the related transfer matrix is given by Zhang et al. [18], according to equation (6).

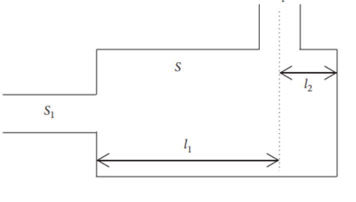


Fig. 6 Diagram of a side outlet muffler [18]

$$[T] = \begin{bmatrix} \cos(kl_1) - \sin(kl_1)\tan(kl_2) & j(c/S)\sin(kl_1) \\ j(S/c)\sin(kl_1) + \cos(kl_1)\tan(kl_2) & \cos(kl1) \end{bmatrix} \tag{6}$$

The problem of the Helmholtz resonator muffler, both in the general version and in the quarter wavelength version, is presented in detail by Lee [20], and in a simplified form by Wu et al. [16]. The relation (7) defines TL using such a solution. The variant with several perforated pipes is approached both theoretically and experimentally in [21], for an application in the automotive field, or by Gerges et al. [22] for general machinery. The change of the wave propagation medium in the Helmholtz resonator was theoretically approached by Ranjbar [23] and shows that TL can increase by 20dB near the fundamental frequency. The determination of flow resistivity for various materials, in order to apply to the mentioned types of resonators, was performed experimentally by Gupta [25]. Such a solution can also be applied to the proposed design by introducing fibers in the volume in which no significant gas flow occurs.

$$TL = 10lg\left[1 + \left(\frac{\sqrt{A_c V/lc}/S_m/2}{f_0/f - f/f_0}\right)^2\right] \tag{7}$$

4. PROPOSED DESIGN

4.1 General description

The proposed silencer solution consists of a propagation path for acoustic waves which is defined by the materialization of a TPMS (Triply Periodic Minimal Surface) type surface. Unlike the noise attenuators presented above, the proposed solution is a combination of a classic muffler, in which the section varies in length (more common in the motorcycle field in the divergent-convergent channel variant) and a perforated straight pipe muffler (which works on the Helmholtz resonator principle).

TPMS type surfaces have a particularity in terms of their integration in a domain: by dividing the domain with such a surface, two distinct volumes are obtained, in which the fluids contained do not mix (unless this is desired, by perforating the wall that delimits them). Such structures are inspired by nature and began to be considered in heat exchangers design [26].

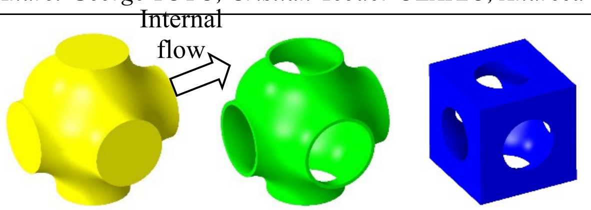
By applying this procedure, two separate volumes are obtained: one in which the actual flow can take place and a volume that is connected to the main volume by means of perforations (Figure 7).

In this way, by using TPMS, two effects are combined, one that leads to a broadband transmission loss (continuous variation of the section), and another that has a considerable efficiency in a limited range of frequencies.

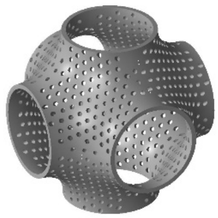
The flow quality is not strongly influenced by the shape of these surfaces, as shown in [26] for small Reynolds numbers, as well as in [27] for large Reynolds numbers. It is true that recirculation zones appear, but these phenomena are present even in the classic mufflers where a sudden variation of pressure occurs or a wall is introduced in the way of the gas flow. Figure 7 shows a single cell, an array of 3 cells or a branch of the existing tubing in a combination of 2x2 lines.

A realistic silencer geometry, using the proposed design, will have many more ramifications, the graphic representation being only an example.

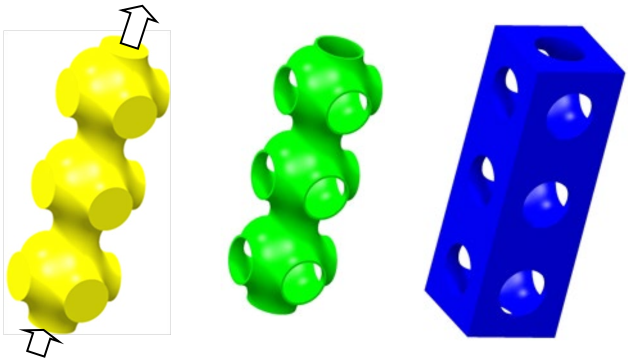
In order to approximate the performance of the new concept, the two phenomena involved in the route must be studied both independently and together: noise attenuation through destructive interference that occurs due to continuous section variation and noise attenuation due to the introduction of a Helmholtz resonator.



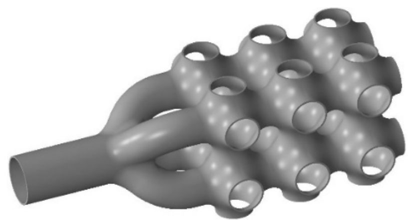
a) 1cell (yellow-flow domain, green-wall, blue-resonance domain)



c) perforated wall



b) multiple cells (yellow-flow domain, green-wall, blue-resonance domain)



d) example of 2x2 rows wall geometry (perforations and flow domains not represented)

Fig. 7 Proposed design (volumes visualisation)

4.2 Theoretical approach

While various numerical methods have been explored for analyzing the acoustic performance of mufflers, the Finite Element Method (FEM) stands out prominently. Since the seminal analyses conducted by Young and Crocker in 1975 up to now[1], FEM programs have been widely employed and have evolved to an advanced stage. These programs exhibit a high level of sophistication, enabling them to predict the acoustic field resulting from the application of solutions with remarkable accuracy. Despite the availability of alternative methods, the FEM remains the most convenient approach, with the transfer matrix method being a notable contender. The transfer matrix method, while advantageous for its relative simplicity in determining transmission loss, has a limitation in its applicability to 1D geometries.

In this context, the geometry presented in Figure 8 serves not only to compare the one-dimensional propagation of acoustic radiation in a vertical plane through the flow channel with a classical configuration but also to hightlight the effectiveness of FEM in capturing the intricacies of acoustic behavior in mufflers. While the Finite Volume Method is recognised for its unique perspective [24], the focus on the advanced capabilities and widespread use of FEM highlights its central role in contemporary acoustic analysis.
It is obvious that the vertical propagation is not analyzed. This should be identical to the horizontal plane for a single row geometry (figure 7b).

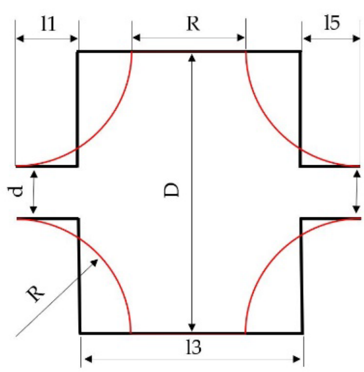


Fig. 8 Analyzed muffler geometries

To define the two-dimentional shape of the proposed design, a circular segment type variation of the wall was used, which almost perfectly fits a section through a single TPMS resulted cell. Three muffler variants have been analysed and presented in Figure 9 (cell dimensions being summarized in Table 1).

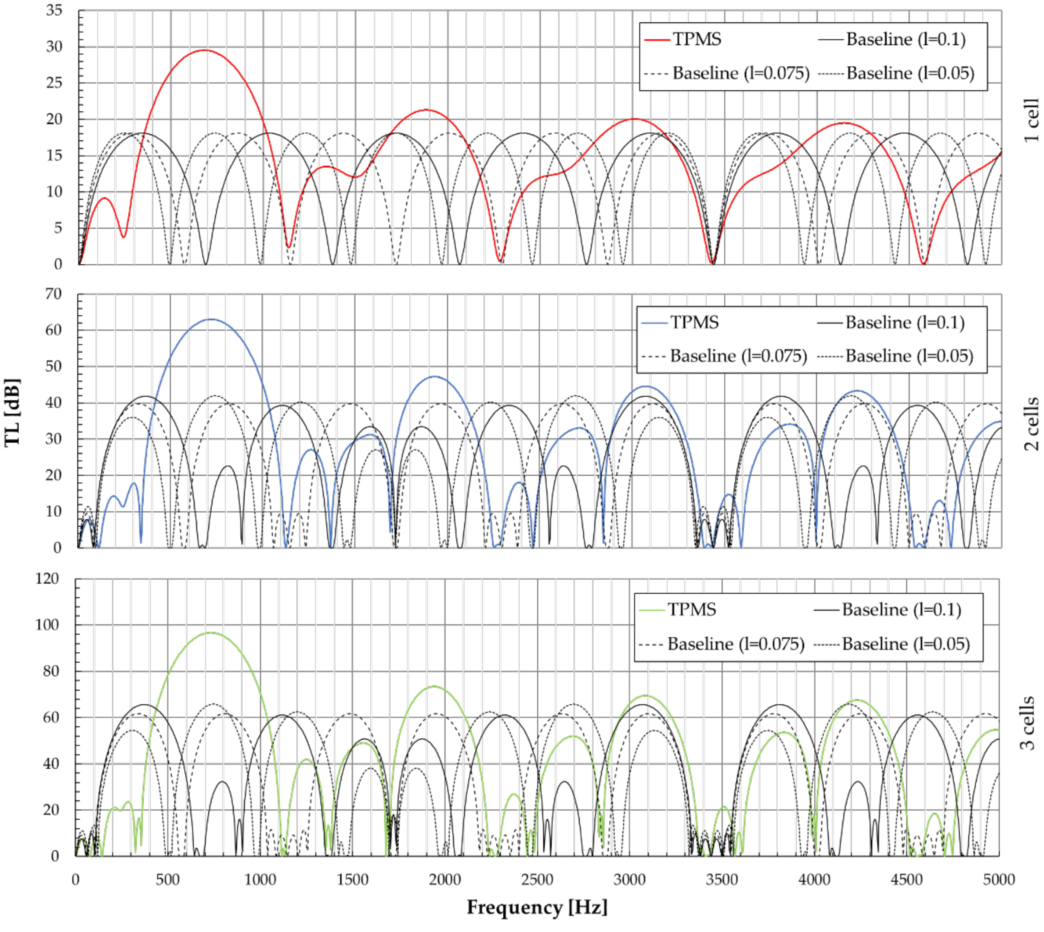


Fig. 9 The results of applying the transfer matrix method

Table 1. Cell dimensions

	TPMS	Baseline (Case1)	Baseline (Case2)	Baseline (Case3)
l1 [m]	-	0.1	0.075	0.05
l3 [m]	-	0.25	0.3	0.35
l5 [m]	-	0.1	0.075	0.05
d[m]	-	0.1	0.1	0.1
D [m]	-	0.4	0.4	0.4
R [m]	0.15	-	-	-

The performance of the rounded wall enclosure was compared with the classical 1D- pipe in pipe configuration. In order to compare the 2 solutions, the length of the smaller pipes was varied (0.05m - 0.1m) so that the enclosure resulting from the sectioning of a TPMS could be compared with a different use of the same available volume. In order to capture the effect of inserting such elements, 2 and 3 cells were placed in series so that the cumulative effect could be observed. Besides the shifting of the maximum attenuation frequencies with the lengthening of the smaller diameter pipe, it is observed for all cases that the highest peaks (with differences of even 20dB in TL at certain frequencies) are found in favour of the proposed geometry. Scaling in one of the directions (flow or perpendicular to it) could help to shift these frequencies. While the current analysis primarily focuses on acoustic aspects, it is crucial to acknowledge the presence of fluid flow within the domain, as evidenced in real-world scenarios [1] This introduces a layer of complexity that necessitates a more comprehensive examination, particularly utilizing specialized programs. A notable precedent is the work conducted in [12] concerning classic mufflers, encompassing configurations with and without baffles and perforations. To delve into the intricacies of the fluid dynamics, a detailed analysis of the flow, akin to studies found in [1], [26], [27], becomes imperative. This is especially pertinent due to the emergence of recirculation areas at both small and large Reynolds numbers. Importantly, considerations should extend beyond mere flow analysis to incorporate insights into instability phenomena. Noteworthy investigations, such as those exploring Kelvin-Helmholtz instability, both with and without the Boussinesq approximation, offer valuable perspectives [28]. Recognizing and addressing these aspects of instability becomes integral for a more comprehensive understanding of the interplay between fluid dynamics and acoustic behavior within the muffler domain.

5. CONCLUSIONS

The main purpose of this paper was to present a new noise attenuator design. It should be mentioned that the solution presented has both advantages and disadvantages. One of the disadvantages is that its shape can be obtained only by additive technologies, there is a limitation in terms of areas of use (especially at very high temperatures). The advantages instead can be substantial, one of them being the ability to integrate into complicated geometries or volumes available in an irregular shape.

The presented analysis has a preliminary form, which wants to present the fact that the noise attenuation by destructive interferences using TPMS type surfaces are comparable to those of the classical designs. Future work will also address numerically (at least 2D) the combination of attenuation obtained by shape variation combined with the introduction of perforations to the other volume. In the future, a small-scale model, made by additive technology, can be analyzed both numerically (using dedicated flow / acoustic software) and experimentally (using a Kundt tube installation) to validate the concept.

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