Article citation info:
Gągorowski A. Analysis of the combustion engine exhaust system structure in aspect of shaping acoustic energy. Combustion Engines. 2023;193(2):112-116. https://doi.org/10.19206/CE-162935

Andrzej GĄGOROWSKI

Combustion Engines
Polish Scientific Society of Combustion Engines

Analysis of the combustion engine exhaust system structure in aspect of shaping acoustic energy

ARTICLE INFO

Received: 12 October 2022
Revised: 28 February 2023
Accepted: 2 April 2023
Available online: 16 April 2023

The flow of exhaust gases is the source of many physical processes, including thermal, acoustic, mechanical and chemical phenomena with high dynamics of changes. The study analyzes the impact of the entire structure of the exhaust system on the formation of acoustic energy, determining the transmission loss characteristics of its individual components and the entire system. On the example of a structure based on a proprietary solution of an adjustable reactive muffler, the possibilities of shaping the flow of acoustic waves in the process of designing and selecting exhaust systems for internal combustion engines were determined. The study was carried out with the use of the CFD method and a specialized package for advanced simulations AVL AST.

Key words: *acoustic energy, transmission loss, exhaust system, combustion engine*

1. Introduction

In recent years, in the area of transport, the priority task has become to reduce the emission of pollutants and noise to a minimum, which is related to the operation of a large number of internal combustion(IC) vehicles in the world. Therefore, promoting the so-called Zero-emission vehicles, including electric cars, is common in the world today and many countries present different visions and plans for the development of this type of construction. It seems, however, that the complete replacement of internal combustion vehicles will be difficult to implement and will cause various types of problems. Therefore, the use of various types of solutions in structures currently in operation can be a very valuable way to solve environmental problems, including minimizing noise emissions to the environment. One of the main sources of noise emission in internal combustion vehicles is the engine-exhaust system [1]. Taking into account the subject of reducing acoustic emissions from motor vehicles, the literature most often includes research focused on dedicated devices, namely acoustic mufflers [2, 3]. In this paper, however, a method of testing the impact of the exhaust system design on the shaping of acoustic energy using the CFD (Computer Fluid Dynamics) method, based on a holistic approach, and not only the testing of a selected element, has been proposed. For this purpose, the entire system was analyzed (including all its devices and connections) on the example of a structure based on a proprietary solution of an adjustable reactive muffler, a detailed description of which is presented in the author's previous works [4, 5]. The main objective of the research was to define the possibility of shaping the flow of acoustic waves in the process of designing and selecting exhaust systems of internal combustion engines. The tests were carried out with the use of computer fluid dynamics and the use of the AVL AST advanced simulation package.

2. Review of the construction of combustion engines exhaust systems

With the development of automotive technology and the desire to increase engine efficiency with the simultaneous task of protecting the environment against pollution and noise, the role of the exhaust system has become a priority in the design of modern internal combustion cars. Exhaust system – an often underestimated element of car engine design fulfills a number of functions that are often contradictory and therefore require optimization of the structure and the use of a compromise [6, 7]. It increases the comfort of traveling from the point of view of noise emission, and at the same time allows the engine to work properly and contributes to the reduction of the amount of harmful substances emitted by the car. The most important tasks of the exhaust system include:

– exhaust gas cleaning and reduction of the content of toxic components,
– reduction of acoustic energy generated during exhaust emissions,
– allowing the most efficient operation of the internal combustion engines (ICE), including providing minimum exhaust resistance allowing maximum engine power.

The end result is the discharge of flue gases into the atmosphere. The car exhaust system consists of many parts, starting with the main devices and ending with smaller elements, but no less important from the point of view of the tasks [6–8]. The main devices of the exhaust system are the exhaust manifold, after-treatment device (ATD) such a catalytic converter (CC) and DPF filter for diesel engines [19], single muffler or group of silencing devices, assembly of piping and connecting elements. Among the remaining parts, we can distinguish various elements to reduce vibrations, connection and assembly elements. The most important assembly parts in the exhaust system are hangers, gaskets, o-rings, clamps, bolts, nuts, flexible couplings and rigid couplings. All parts constitute a whole, allowing for proper and safe use of the car by ensuring the desired operational parameters and limiting the negative impact on people and the environment.

When reviewing various car designs, we can notice the variety of shapes and structures of individual devices, as well as differences in their arrangement in the exhaust system [6–8]. The catalytic converter as a device for exhaust gas treatment should be installed as close to the engine as possible in order to achieve the operating temperature in a sufficiently short time and thus obtain the effectiveness of chemical processes [9, 18]. However, its actual location (as well as other devices) depends on the space available under the vehicle. The outer shape of the reactor body is most often triangular, oval or round. The ATD unit can also affect the acoustical performance of an exhaust system. From the point of view of the objectives of this paper, the "acoustic effect" closely related to the internal structure of the converter, which is formed by the honeycomb structure, is particularly important. On the other hand, its main goal is to reduce the toxic components contained in the exhaust gas, which is ensured by chemical compounds (catalytically effective materials) and precious metals covering the walls of the pipe structure, which react chemically with exhaust gases [9–11].

The construction material used is also important for the processes taking place inside the converter structure. Due to the material used for construction, we distinguish two types of catalysts: ceramic catalysts (with a ceramic block) and metal catalysts (with a metal block). In the design of the exhaust system, the catalyst must be carefully tuned, because a high level of flow resistance has a significant impact on the engine's operating characteristics [9]. On the other hand, as a result of the flow through narrow, ceramic and numerous channels in the monolith, numerous sources of sound and vibrations can be created [12]. Such a structure causes that the catalytic device also acts as a reactive damper that allows reducing exhaust gas pulsations. The shape and structure of the inlet converter should be designed so that the exhaust gas flows evenly through the monolith. The alternative metal catalyst has a structure made of a thin, crimped metal foil wound and soldered into a high-temperature system. As with a ceramic catalyst, the surface is coated with a catalytically effective material. Due to the thin wall, more channels can be distributed in the same area. This means a certain resistance to the effects of exhaust gases, which is beneficial from the point of view of optimizing the efficiency of the converter at high engine operating parameters [13].

The exhaust system mufflers, as devices dedicated to the reduction of acoustic energy in a specific frequency range, have been described in many references, and their design solutions can be very different [2, 3]. The construction uses two physical principles of shaping acoustic waves, reflection and absorption. That is why silencers can be divided into two main groups according to the above-mentioned principles, i.e. reactive and absorption silencers. Their efficiency is usually satisfactory in a narrow frequency band. Therefore, the third used group consists of reactive-absorption mufflers, which are a combination of the above-described structures – allowing to use the advantages and properties of reducing acoustic energy in a wider frequency band. A more detailed review of various muffler solutions can be found in [14].

As shown by the author's research [15], the geometry of the exhaust system, including individual elements and connection channels, as well as their dimensions and shape, are important for the formation of acoustic processes. Adjusting the geometry of the exhaust system to the chassis structure of a specific motor vehicle model requires the use of both straight and curved connecting segments. Solutions include arcs and bends of various shapes and geometries, including angular and wave elements, as well as arcs and curves with variable deflection angles.

To sum up, by using various structural elements in the exhaust system of an internal combustion engine and specific geometrical parameters, it is possible to shape acoustic energy influencing its flows on the engine-environment path in various ways. In the next chapter, an attempt was made to determine the degree of influence on the formation of acoustic processes for individual devices and for the entire system.

3. Development of models of the exhaust system and its components

They take into account the basic goal described in the introduction to this paper and, based on the theory presented in the previous chapter, a model of the exhaust system was built, containing all the basic elements, and then its parameterization was performed. The specialized AVL AST package was used to achieve the above goals. The model of the exhaust system with a power unit is shown in Fig. 1a. Its main geometric parameters are presented in Table 1.

a)

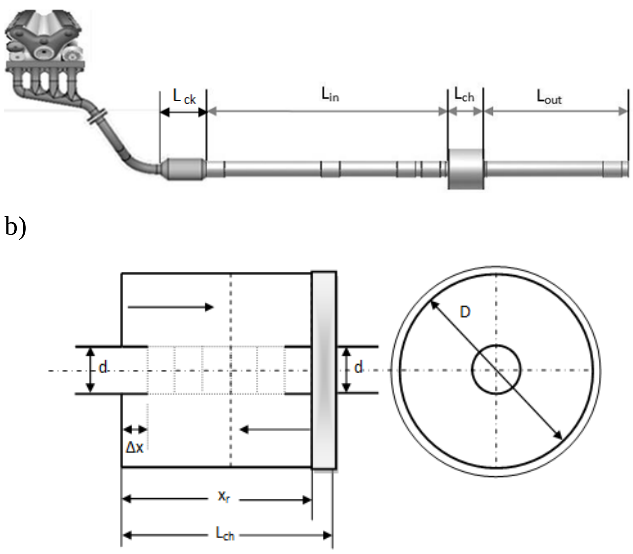

Fig. 1. Exhaust system model a) in combination with the engine b) muffler structure model with an expansion chamber (D) and inlet adjustment with a diameter (d)

The exhaust system model uses a proprietary design of a muffler with a variable structure (Fig. 1b, Table 2). The system belongs to the group of reactive systems and enables the change of the internal structure by gradual (with the assumed step Δx) control of the extended input (x_r) within the scope limited by the length of the main expansion chamber (L_{ch}).

According to the theory of gas dynamics [16], changes in the internal structure of the system cause a variable flow of the gaseous medium (in this case exhaust gases), e.g. by creating a pressure difference at the boundary of certain areas. From the point of view of the analysis of acoustic energy [16, 17], we deal with changes in the flow resistance and acoustic pressure, as well as the velocity and direction of the flow. As a result, the acoustic energy passing through the system can be reduced or increased by incorporating further acoustic discontinuities with different resistance into the basic system.

Table 1. Geometric parameters of connection segments in the exhaust system model

Parameter and unit	Value
The diameters of the middle, inlet and outlet channels downstream the catalyst [mm]	51
Connection diameters in front of the catalyst [mm]	35.5
The length of the segment in front of the catalyst (inlet part) [mm]	400
The length of the exhaust system – central duct, L_{in} [mm]	1310
The length of the exhaust system – end duct, L_{out} [mm]	450

Table 2. Selected parameters of the muffler with the variable structure

Parameter name and unit	Value
x_r [mm]	$\Delta x \le x_r \le 100$
Δx [mm]	$0 < \Delta x < 100$
d [mm]	51
D [mm]	130
L_{ch} [mm]	110

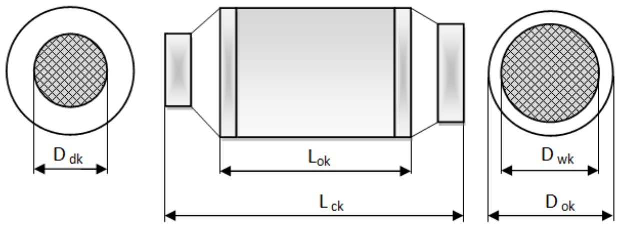

Fig. 2. Model of a catalytic reactor

In the catalyst model, the geometrical parameters of which are shown in Fig. 2, the outer shape of the body (housing) with a circular cross-section was assumed. The monolith placed in it has a "honeycomb" structure with channels visible in Fig. 2 (side views). From the point of view of the objectives of this paper, the "acoustic effect" closely related to the internal structure of the converter, which is created by the system of parallel channels, is particularly important. The kinetic model was developed using the AVL BOOST software. The catalyst parameters used in the construction of the model are presented in Tables 3 and 4. The temperature measured in the center of the monolith was used for the simulation. A monolith model with square-section channels was used. Each channel was digitized in the axial direction using 20 mesh points with a grid aspect ratio of one. Mass transfer through the boundary layer was considered using the Darcy model [17]. The parameters of the monolith sample with the square cell specification used in the simulation tests are described in Table 3.

Table 3. Parameters of the monolith sample (square cell type specification) used in the simulations

Parameter name and unit	Value
Cell density, CPSI [in^2]	400
Wall thickness, δ_{wall} [mm]	0.34
Diameter of monolith sample [mm]	21
Monolith sample length [mm]	20
Catalytic material porosity [%]	0.5

The geometric parameters adopted in the catalytic reactor model are shown in Table 4.

Table 4. Geometric parameters adopted in the catalytic reactor model

Parameter name and unit	Value
Housing diameter, D_{ok} [mm]	60
Housing length, L_{ok} [mm]	160
Monolith length, L_{mk} [mm]	150
Duct diameter, L_{kk} [mm]	1
Inlet diameter, D_{dk} [mm]	35.5
Outlet diameter, D_{wk} [mm]	51
Total length, L_{ck} [mm]	200

As mentioned in the previous chapter, the generation and type of acoustic phenomena are influenced by the geometry of the exhaust system, including the individual connecting elements. Therefore, the research also included an exemplary model of the arc segment between the exhaust manifold and the catalytic converter as an alternative to the straight connection (Fig. 3).

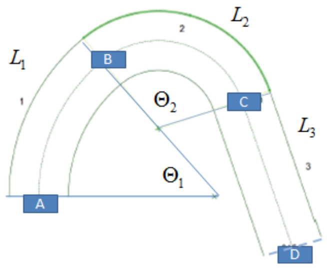

Fig. 3. Model of curvature for a cylindrical segment

In the curvature model, the connecting segment is divided into Li sections of different curvature (L1-AB, L2-BC, L3-CD,). The deflection angle for the ith segment is described in Table 5.

Table 5. Geometric parameters adopted in the curvature model

Parameter and unit	Value
Θ_1 [°]	50
Θ_2 [°]	100

4. Study on the influence of the exhaust system design on the formation of acoustic energy

Using the models described in the previous chapter, tests of the exhaust system were carried out with the use of the computer method of fluid analysis CFD. A 4-stroke internal combustion engine model was adopted as the drive unit. The model of the exhaust gas flow in the engine – exhaust system was built in the AVL AST (Advanced Simulation Tools) software environment, taking into account the AVL BOOST module for the calculation of acoustic flows. At individual stages of the research, various changes were made to the structure of the system in order to analyze the degree of influence of individual devices, as well as the geometry of connection elements on the dynamic flows of acoustic energy through its individual segments.

Table 6 shows the selected reference (initial) parameters and the boundary conditions adopted for the calculations, taking into account the operating cycle of a four-stroke internal combustion engine (SI). At the moment of starting the opening of the exhaust valve, the exhaust gas is "ejected", and a characteristic phenomenon is the formation of overpressure pulses. These pulses travel along the system. The flow speed depends on the set engine speed. The control of the fuel mixture is determined by the ratio of air to fuel (A/F).

The calculations carried out, taking into account various variants of the exhaust system, allowed to determine, among others values of pressure and velocity of local flows in specific sections of the engine – exhaust system as a function of time, and then assess the attenuation in the assumed frequency domain (0–5000 Hz).

Table 6. Selected reference parameters and boundary conditions

Parameter name and unit	Value
Rotation speed n [rpm]	1200
A/F	14.5
Pressure p [MPa]	0.1013
Temperature T [^{o}C]	20.85

In the work, to analyze the impact of changes in connections and individual devices on the level of transmitted acoustic energy, the indicator determining the transmission loss (TL) in the system was used. Transmission loss was defined as the difference between the sound power levels (W) of the sound determined at the beginning and at the end of a selected section of the exhaust system [15]:

$$TL = 10\log\frac{W_{in}}{W_{out}} \quad (1)$$

The sound power level in the given section A of the system can be defined as follows:

$$W_i = \int_A \frac{|p^2|}{2\rho c} dA \quad (2)$$

where: p – pressure amplitude in the tested cross-section of the system, ρ – exhaust gas density, c – speed of sound.

Figure 4–6 for the tested frequency range (0–5000 Hz) and for three selected stages of acoustic attenuator input extension adjustment (x_{r1} = 10 mm, x_{r2} = 100 mm, x_{r3} = 40 mm) show examples of the results of the transmission loss level reflecting changes in acoustic energy for the entire exhaust system. The following figures show the waveforms of the transmission loss, respectively for the exhaust system:

– with a regulated muffler, but without a catalytic converter, and with straight-line connections (Fig. 4),
– with a regulated muffler and a catalytic converter and using straight segments (Fig. 5),
– with a regulated muffler and catalytic converter, and with a curved segment in accordance with the adopted deflection model (Fig. 6).

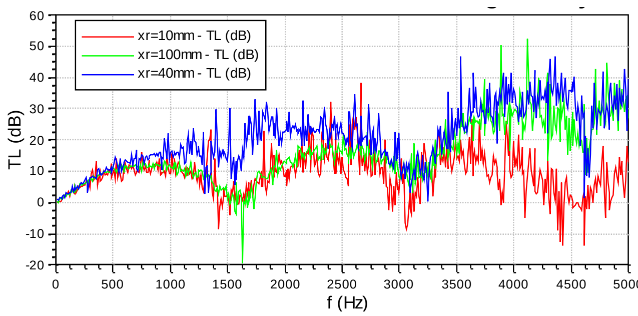

Fig. 4. Comparison of the transmission loss in the system with the regulated muffler without the catalytic converter

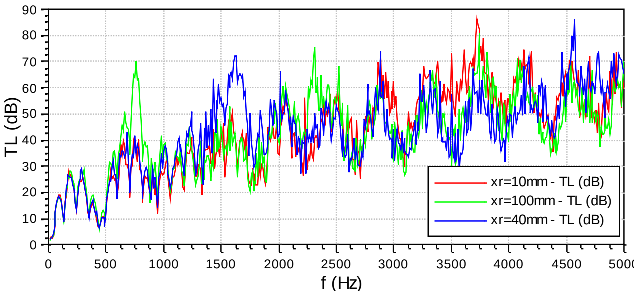

Fig. 5. Comparison of the transmission loss with the use of a straight segment in the system with the muffler and the catalytic converter for the three settings of the input extension (x_r)

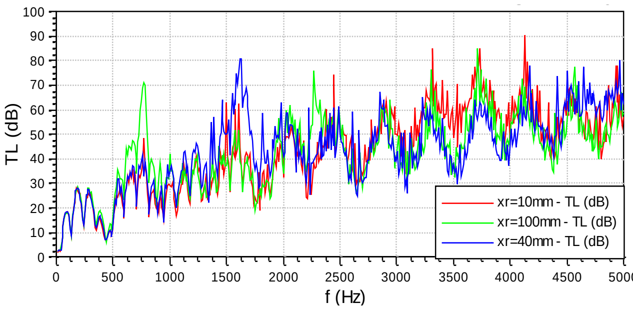

Fig. 6. Comparison of the transmission loss with the use of the arc segment and with the muffler and catalytic converter for the three x_r input extension settings

By analyzing the waveforms of the transmission loss parameter as a function of frequency, it can be concluded that the use of different designs of exhaust systems causes significant changes in terms of acoustic energy attenuation. In the examples of the results shown in Fig. 4–6 for the three design variants, quite significant differences in the TL values can be noticed, taking into account the fact that we are dealing with the decibel scale. The example in Fig. 4, representing the system with the muffler only, shows that even a small change in the internal structure of the system (e.g. changing the x_r input extension from 10 mm to 40 mm) causes quite significant changes in the entire tested frequency range. On the other hand, in the case of introducing into the structure of the exhaust system of the catalytic converter (Fig. 5), we can observe in many areas a strong enhancement of the transmission loss level. It can therefore be concluded that the catalyst has a strong influence on the transfer of acoustic energy in the system, which is consistent with the theory presented in Chapter 2. The use of a curvilinear element (Fig. 6) in the form of an arc connection between the exhaust manifold and the catalyst causes significant changes only in some frequency ranges in relation to the classical system with a straight connecting segment (Fig. 5).

Comparing all the analyzed design cases of the exhaust system, a large variability of the TL level waveforms in all the graphs can be noticed, which is manifested in significant differences in individual frequency areas, both in terms of bandwidth and the value of the transmission loss.

5. Summary

The design of the exhaust system has a considerable influence on car emissions, engine performance and exhaust acoustics. The paper presents the results of research on the development of acoustic energy in the engine-exhaust system. A method of analyzing the impact of the structure using the CFD method was proposed, based on a holistic approach, not just the study of a selected element. The sample results presented in the article prove the great possibilities of shaping acoustic energy, pointing to its extreme levels when we apply a specific design of the exhaust system. The conducted research has shown that the sources of the formation and shaping of acoustic energy in the process of exhaust gas flow require an analysis of the structure of the entire exhaust system. The obtained results of the attenuation level in individual sections of the system made it possible to compare the waveforms in a wide frequency range and show the high dynamics of changes in the level of acoustic energy.

In the process of analyzing the entire exhaust system, a large possible range of changes in acoustic energy was demonstrated. The obtained results indicate the need for detailed further tests to validate the method taking into account other car constructions. This will confirm the correctness of its use in the process of designing the chassis of a car, taking into account the optimal design of the exhaust system to meet the acoustic requirements (in terms of reducing noise emissions to the environment).

Acknowledgements

The research has been conducted in the international program: "AVL AST University Partnership Program" (AVL, Graz, Austria).

Nomenclature

CFD	computer fluid dynamics	ATD	after-treatment device
IC	internal combustion	DPF	diesel particulate filter
ICE	internal combustion engine	CC	catalytic converter
SI	Spark Ignition	CPSI	cell per square inch
TL	transmission loss	A/F	air fuel

Bibliography

[1] Bender EK, Brammer AJ. Internal combustion engine intake and exhaust system noise. J Acoust Soc Am. 1975;58:1-22. https://doi.org/10.1121/1.380651

[2] Ji Z, Ma Q, Zhang Z. Application of the boundary element method to predicting acoustic performance of expansion chamber mufflers with mean flow. J Sound Vib. 1994;173: 57-71. https://doi.org/10.1006/jsvi.1994.1217

[3] Selamet A, Lee IJ, Huff NT. Acoustic attenuation of hybrid silencers. J Sound Vib. 2003;262(3):509-527. https://doi.org/10.1016/S0022-460X(03)00109-3

[4] Gągorowski A. Badania wybranych struktur tłumików układów wydechowych w środowisku AVL. Prace Naukowe Politechniki Warszawskiej. Transport. 2016;112:101-110.

[5] Gągorowski A. Modeling of adjustable muffler in the exhaust system of an internal combustion engine. Research Methods and Solutions to Current Transport Problems, Advances in Intelligent Systems and Computing. 2020:124-132. https://doi.org/10.1007/978-3-030-27687-4_13

[6] Kesgin U. Study on the design of inlet and exhaust system of a stationary internal combustion engine. Energ Convers Manage. 2005;46(13-14):2258-2287. https://doi.org/10.1016/j.enconman.2004.10.015

[7] Smith PH, Morrison JC. The scientific design of exhaust and intake systems. R. Bentley Cambridge, Mass. 1971.

[8] Winterbone DE, Pearson RJ. Theory of engine manifold design, Wave action methods for IC engines. Professional engineering publishing. 2000.

[9] Sjoblom J, Papadakis K, Creaser D. Use of experimental design in development of a catalyst system. Catal Today. 2005;100(3-4):243-248. https://doi.org/10.1016/j.cattod.2004.09.066

[10] Grzybowiska-Świerkosz B. Elementy katalizy heterogennej. Wydawnictwo Naukowe PWN. 1993.

[11] Perry R, Green D. Perry's chemical engineers handbook, 6th edn. McGraw Hill Book Company. 1984.

[12] Lavrentjev J, Rämmal H, Tiikoja H. The passive acoustic effect of automotive catalytic converters. SAE Technical Paper 2011-24-0219. 2011. https://doi.org/10.4271/2011-24-0219

[13] Koltsakis GC, Konstantinidis PA, Stamatelos AM. Development and application range of mathematical models for 3-way catalysts. Appl Catal B-Environ. 1997;12(2-3):161-191. https://doi.org/10.1016/S0926-3373(96)00073-2

[14] Gągorowski A, Melon A. Selected aspects of modelling mufflers for exhaust systems of vehicles. Journal of KONES. 2013;20(2):97-103.

[15] Gągorowski A. Badanie wybranego połączenia w układzie wylotowym z uwzględnieniem analizy akustycznej. Prace Naukowe Politechniki Warszawskiej. Transport. 2018;121: 57-66.

[16] Rathakrishnan E. Applied gas dynamics. John Wiley and Sons. 2010.

[17] Lage JL. The fundamental theory of flow through permeable media from Darcy to turbulence. Transport Phenomena in Porous Media. 1998:1-30.

[18] Kozioł-Jarosz M, Brzeżański M. The role and tasks of the support mats in the construction of catalytic converters. Combustion Engines. 2017;170(3):96-99. https://doi.org/10.19206/CE-2017-315

[19] Johnson TV, Joshi A. Directions in vehicle efficiency and emissions. Combustion Engines. 2016;166(3):3-8. https://doi.org/10.19206/CE-2016-306

Andrzej Gągorowski, DEng. – Faculty of Transport, Warsaw University of Technology, Poland.
e-mail: *andrzej.gagorowski@pw.edu.pl*