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Research Article

Maximum Sound Transmission Loss in Multi-Chamber Reactive Silencers: Are Two Chambers Enough?

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Keywords

Primary subject classification, reactive silencer, noise, transmission loss, multi-chamber, baffle number.

Abstract

The transmission loss performance of multi-chamber silencer with respect to its number of chambers is studied. At this regard, theoretical values of sound transmission loss (STL) for various geometries of silencers with different number of baffles have been calculated by the transfer matrix method. Also, the sound transmission loss for the considered models have been measured experimentally. The main aim is to find the effect of number of chambers on the performance of silencers. Indeed, the target is to find the best number of chambers so that it can lead to the maximum sound transmission loss. It is realized that by increasing the number of chambers, the sound transmission loss can be improved. However, this can be happened when the number of baffles is not more than three. Because after that, the increasing of baffles has not a significant effect on the maximization of the transmission loss. It is confirmed that a silencer with two chambers is well enough to enjoy from the highest sound transmission loss over the frequency range of 0 to 3000 Hz. The length of baffles is important according to the considered frequency ranges. If the maximization of transmission loss over the low frequency ranges is on demand, the length of the first chamber should be more than others. However, for high frequency ranges the length of the second chamber should be more.

1. Introduction

Design of multi-chamber mufflers for noise transmission loss maximization has been always on demand to its wide range of applications in various industrial sectors. The sound attenuation of perforated dissipative circular mufflers including a folded resonator and a short expansion chamber was investigated in detail by means of a two-dimensional asymmetrical analytical approach based on the mode matching technique by Denia et al. [1]. Research on new techniques of single-chamber plug-inlet

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mufflers was addressed by Chiu [2]. In another work by Chiu [3], both the numerical decoupling technique and simulated annealing (SA) algorithm for solving the coupled acoustical problem of perforated plug-inlet tubes and optimizing the muffler shape were used. Later, a research work on multi-chamber mufflers conjugated with open-ended perforated intruding inlet tubes was presented by Chang [4]. Chang and Chiu [5] did a numerical analyze and maximized the acoustical performance of a muffler within a limited space. In a work by Allam [6], the four-port system matrix for two wave guides coupled via the micro perforated panels (MPP) tube was derived and used to compute the two-port transfer matrix for an expansion chamber muffler. An optimal partition layout inside an expansion chamber muffler with an offset inlet/outlet was systematically designed by using topology optimization to achieve the desired characteristics in terms of acoustics and fluid mechanics by Jang and Lee [7]. A muffler composed of multiple rectangular fin-shaped chambers was proposed by Chiu et al. [8]. An analysis of the sound transmission loss of two-chamber mufflers with multiple parallel perforated plug tubes was presented by Chiu [9]. The noise behavior of the blower used on fuel cell vehicles was measured and analyzed by Xiang et al. [10]. Finding the best design for structural acoustics applications is a difficult task. There are many publications in this field. For example, a series of publications by Ranjbar et al. [11-16] showed various aspects of multidisciplinary engineering design optimization of complex structures like mufflers and exhaust systems.

Selamet et al. presented an article entitled as acoustic attenuation of hybrid silencers [17]. Multi-dimensional boundary element method predictions of a hybrid silencer demonstrated that a reactive component such as a Helmholtz resonator can improve transmission loss at low frequencies and a higher duct porosity may be effective at higher frequencies.

Comparison of 1-D transfer matrix method and finite element method with tests for acoustic performance of multi-chamber perforated resonator was done by Guo et al. [18]. They showed that the accuracy of TMM in low frequency ranges can be affected by the perforation. However, the speed of modelling and STL calculation by TMM is an advantage.

Xiang et al. did a study on multi-chamber micro-perforated muffler with adjustable transmission loss [19]. They proposed a muffler which was effective and efficient to attenuate the low-medium frequency wide band noise and the narrow band harmonics simultaneously.

Arslan et al. investigated the effect of position and the number of the baffles on sound transmission loss using theoretical, numerical and experimental studies [20].

It is a common practise to divide the chamber of length L into two parts to study the effect of partitioning or baffles on the STL performance. The longer sub-chamber is used to control low-frequency noise whilst the shorter chamber is used for controlling higher frequencies. Dividing the chamber into three or more sub-parts does not really help in obtaining an extra advantage. This paper aims to cover the effect of baffles and chambers on the maximization of STL. In next section, the theoretical and experimental investigation of best design for a multi-chamber silencer are presented.

2. Modeling

In this section, the calculation of STL of a circular multi-chamber silencer is presented. In the case of planar acoustic waves, acoustic pressure, particle velocity, particle position and instantaneous density change are constant on the same plane. If the diameter of the pipe forming the muffler is smaller than half of the wavelength, then the plane wave acceptance is appropriate [21]. This means that for the acoustic frequency range up to 3000 Hz, the pipe diameter should be smaller than 56 mm in the analyzes. Figure 1 shows the general geometry of model. Furthermore, the 3-dimensional view of the general model is represented in figure 2.

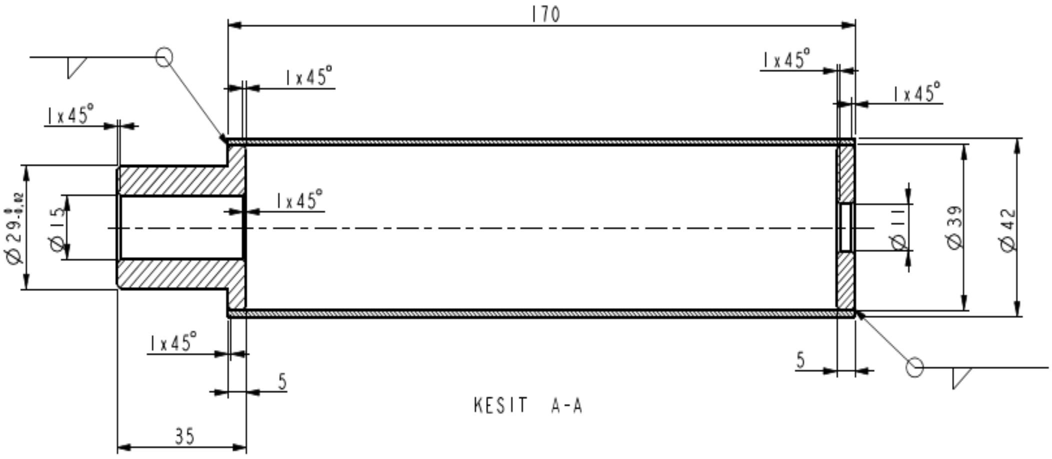

Figure 1. The general geometry of silencer

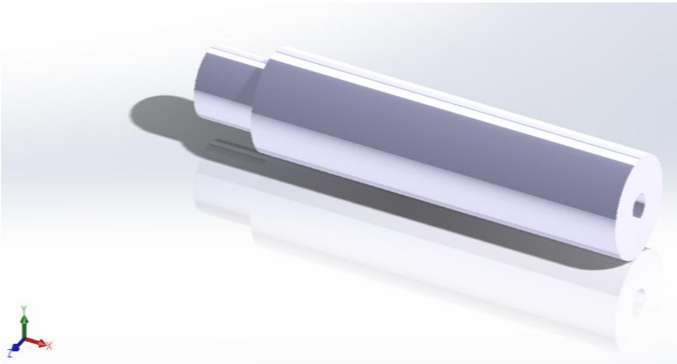

Figure 2. The three-dimensional model of general silencer.

Figure 3 shows the silencer model with one baffle in the middle of its chamber. The general idea is to investigate the effect of baffles and their locations on the sound transmission loss maximization of silencers.

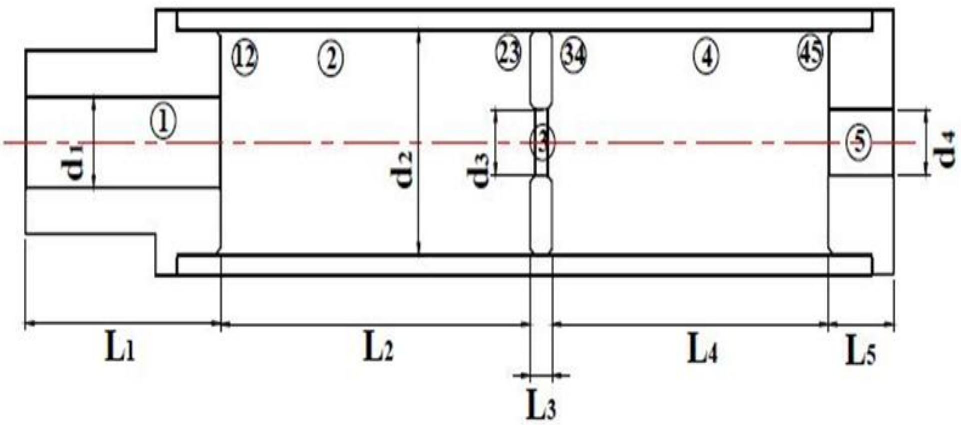

Figure 3. The silencer model with one baffle.

In practice, a silencer consists of several interconnected elements. Figure 3 shows the geometry of a multi-chamber silencer. The pipe diameters and lengths are known. The wave number k is a function of the speed of sound at room temperature and the sound frequency (f). In figure 1, part numbers "1-5" are the straight pipes while the part numbers "12 and 34" are sudden expansion with extension pipe and part number "23 and 45" are sudden constriction with extension pipe.

For a silencer with one baffle when M is the Mach number in each part of silencer,

$$M_2 = M_1 \frac{S_1}{S_2},\ M_3 = M_2 \frac{S_2}{S_3},\ M_4 = M_3 \frac{S_3}{S_4},\ M_5 = M_4 \frac{S_4}{S_5} \tag{1}$$

S is the cross-sectional area, d is the diameter and l are the length,

$$S_1 = \frac{\pi d_1^2}{4},\ S_2 = \frac{\pi d_2^2}{4},\ S_3 = \frac{\pi d_3^2}{4},\ S_4 = \frac{\pi d_4^2}{4},\ S_5 = \frac{\pi d_5^2}{4} \tag{2}$$

where d_1 is diameter of straight pipe 1, d_2 is diameter of straight pipe 2, d_3 is diameter of straight pipe 3, d_4 is diameter of straight pipe 4 and d_5 is the diameter of straight pipe 5 and c is the speed of sound. Furthermore, the wave number k_0 can be calculated as;

$$k_0 = \frac{\omega}{c} = \frac{2\pi f}{c} \tag{3}$$

The acoustic impedance (Y) of each part of silencer can be calculated as,

$$Y_1 = \frac{\rho_0 . c}{S_1},\ Y_2 = \frac{\rho_0 . c}{S_2},\ Y_3 = \frac{\rho_0 . c}{S_3},\ Y_4 = \frac{\rho_0 . c}{S_4},\ Y_5 = \frac{\rho_0 . c}{S_5} \tag{4}$$

while k_c is the wave number,

$$k_c = \frac{k_0}{(1 - M_1^2)} \tag{5}$$

Here, the transfer matrix for straight pipe part number “1” as;

$$T_1 = \begin{bmatrix} e^{(-i.M_1.k_c.l_1)} \mathrm{Cos}(k_c.l_1) & i.Y_1 e^{(-i.M_1.k_c.l_1)} \mathrm{Sin}(k_c.l_1) \\ \frac{i}{Y_1} e^{(-i.M_1.k_c.l_1)} \mathrm{Sin}(k_c.l_1) & e^{(-i.M_1.k_c.l_1)} \mathrm{Cos}(k_c.l_1) \end{bmatrix} \tag{6}$$

The transfer matrix for sudden expansion straight pipe part number “12” as;

$$T_{12} = \begin{bmatrix} 1 & (1 + K_{d12}) M_2 Y_2 - M_1 Y_1 \\ 0 & 1 \end{bmatrix} \tag{7}$$

K_{d12} static pressure loss constant;

$$K_{d12} = \left(\frac{S_1}{S_2} - 1 \right)^2 \tag{8}$$

For straight pipe part number ”2” the transfer matrix is;

$$T_2 = \begin{bmatrix} e^{(-i.M_2.k_c.l_2)} \mathrm{Cos}(k_c.l_2) & i.Y_{02} e^{(-i.M_2.k_c.l_2)} \mathrm{Sin}(k_c.l_2) \\ \frac{i}{Y_{02}} e^{(-i.M_2.k_c.l_2)} \mathrm{Sin}(k_c.l_2) & e^{(-i.M_2.k_c.l_2)} \mathrm{Cos}(k_c.l_2) \end{bmatrix} \tag{9}$$

The transfer matrix for sudden contraction straight pipe part number “23” as;

$$T_{23} = \begin{bmatrix} 1 & (1 + K_{d23}) M_3 Y_3 - M_2 Y_2 \\ 0 & 1 \end{bmatrix} \tag{10}$$

K_{d23} static pressure loss constant;

$$K_{d23}=\left(\frac{1-\frac{S_3}{S_2}}{2}\right) \tag{11}$$

For straight pipe part number "3" the transfer matrix is;

$$T_3=\begin{bmatrix} e^{(-i.M_3.k_c.l_3)}\,\mathrm{Cos}(k_c.l_3) & i.Y_{03}e^{(-i.M_3.k_c.l_3)}\,\mathrm{Sin}(k_c.l_3) \\ \frac{i}{Y_{03}}e^{(-i.M_3.k_c.l_3)}\,\mathrm{Sin}(k_c.l_3) & e^{(-i.M_3.k_c.l_3)}\,\mathrm{Cos}(k_c.l_3) \end{bmatrix} \tag{12}$$

The transfer matrix for sudden expansion straight pipe part number "34" as;

$$T_{34}=\begin{bmatrix} 1 & (1+K_{d34})M_4Y_4-M_3Y_3 \\ 0 & 1 \end{bmatrix} \tag{13}$$

K_{d34} static pressure loss constant;

$$K_{d34}=\left(\frac{S_3}{S_4}-1\right)^2 \tag{14}$$

For straight pipe part number "4" the transfer function is;

$$T_4=\begin{bmatrix} e^{(-i.M_4.k_c.l_4)}\,\mathrm{Cos}(k_c.l_4) & i.Y_{04}e^{(-i.M_4.k_c.l_4)}\,\mathrm{Sin}(k_c.l_4) \\ \frac{i}{Y_{04}}e^{(-i.M_4.k_c.l_4)}\,\mathrm{Sin}(k_c.l_4) & e^{(-i.M_4.k_c.l_4)}\,\mathrm{Cos}(k_c.l_4) \end{bmatrix} \tag{15}$$

The transfer matrix for sudden contraction straight pipe part number "45" as;

$$T_{45}=\begin{bmatrix} 1 & (1+K_{d45})M_5Y_5-M_4Y_4 \\ 0 & 1 \end{bmatrix} \tag{16}$$

K_{d45} static pressure loss constant;

$$K_{d45}=\left(\frac{1-\frac{S_5}{S_4}}{2}\right) \tag{17}$$

For straight pipe part number "5" the transfer function is;

$$T_5=\begin{bmatrix} e^{(-i.M_5.k_c.l_5)}\,\mathrm{Cos}(k_c.l_5) & i.Y_{04}e^{(-i.M_5.k_c.l_5)}\,\mathrm{Sin}(k_c.l_5) \\ \frac{i}{Y_{05}}e^{(-i.M_5.k_c.l_5)}\,\mathrm{Sin}(k_c.l_5) & e^{(-i.M_5.k_c.l_5)}\,\mathrm{Cos}(k_c.l_5) \end{bmatrix} \tag{18}$$

Total transfer matrix;

$$T=[T_1].[T_{12}].[T_2].[T_{23}].[T_3].[T_{34}].[T_4].[T_{45}].[T_5] \tag{19}$$

$$T = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \tag{20}$$

Then, the sound transmission loss (STL) for the model with one baffle and therefore two chambers are,

$$STL = 20\log\left[\left(\frac{Y_5}{Y_1}\right)^{1/2} \frac{1(1+M_1)}{2(1+M_5)}\left|T_{11} + \frac{T_{12}}{Y_5} + T_{21}Y_1 + T_{22}\frac{Y_1}{Y_5}\right|\right] \tag{21}$$

The STL for the silencer with two baffles is then

$$STL = 20\log\left[\left(\frac{Y_7}{Y_1}\right)^{1/2} \frac{1(1+M_1)}{2(1+M_7)}\left|T_{11} + \frac{T_{12}}{Y_7} + T_{21}Y_1 + T_{22}\frac{Y_1}{Y_7}\right|\right] \tag{22}$$

In the same way, the STL for the models with more baffle numbers can be determined. In next section, the experimental and theoretical results for STL of silencers with several baffles are presented.

To examine the ideal silencer geometry with respect to noise emission reduction, 25 experiments were done by changing the number and position of the silencer baffles. The measurements were made in the laboratory using the STL experimental setup as it is shown in Figure 4.

The transfer matrix is calculated from the particle velocity and sound pressure, i.e. the acoustic impedance of the advancing waves at both ends of the silencer. Basically, the separation of the stable waves by simultaneous data collection from four microphones is to investigate the relative amplitude and phase values of the advancing waves. Transmission loss values are calculated by the transfer matrix method. While two measurements are carried out in the experiment, the muffler outlet is open to the atmosphere while the silencer end is closed with an absorber material.

3. Experimental Setups

The general experimental setup for the measurement of the noise reduction performances of mufflers are shown in figures 4 to 5. The general setup for the measurement of sound transmission loss is shown in figure 4. The elements of experimental setup are indicated in figure 5. 25 experiments were carried out by changing the number and location of the muffler. In order to examine the ideal noise reduction, the measurements were made in the laboratory environment using the experimental setup which is shown in Figure 4.

Figure 4. General view of the experimental setup.

The STL measurement test device, which is specially designed for the silencers, includes the impedance tube, speaker, amplifier, data acquisition card, microphones, calibrator and fittings, as seen in figure 6. In order to investigate acoustical performance of the gun suppressors experimentally, an experimental setup was established. Experimental setup for the gun suppressor transmission loss measurement was consists of an impedance tube, a speaker, an amplifier, an analyzer, four microphones, a calibrator and connecting parts. Tang Band W4-930SF model speaker and Sure Electronics 2x15 W TA2024 digital amplifiers was used in order to send the noise signal to the impedance tube from the computer. The band width of the amplifier was between 20 Hz and 20 kHz and signal to noise ratio was 90 dB. The control of the system was made by the analyzer National Instruments USB 4431. Besides, four-piece IEPE types G.R.A.S. Type 46BD microphones were used in order to measure the sound pressure levels. G.R.A.S. 42AB type calibrator was used to calibrate the microphones. The calibrator generates 114 dB sound pressure level at 1000 Hz frequency when pushing the button on the calibrator.

a) Speaker

b) Analyzer

c) Microphone

d) Microphone Calibration Device

Figure 5. Elements of STL experimental measurement setup.

For the same silencer prototype as the experimental setup, two experiments were performed, provided that the conditions remained the same. Here, the repeatability of the test setup is tested. The STL results of a curtain silencer where the curtain was placed in the middle of the curtain were obtained before the repeatability test could be performed. It was determined that the experiments performed by repeating twice for the silencer gave very close results. This shows that the test device is reliable in terms of repeatability.

4. Results

Table 1 shows several various silencer geometries with different baffle numbers. Totally, 25 models could be tested experimentally and therefore they are reported. Seven silencers with one baffle but different geometries are investigated. Also, five silencer models with two baffles are tested. Moreover, five silencer models with three baffles are examined. Furthermore, three silencer models with four baffles are experienced. Later, three silencers with five baffles, one silencer with six baffles and one silencer with seven baffles are studied. There are several reasons for considering of different models for each number of baffle as it is harder to build a silencer with several baffles plus some technical reasons which will be discussed in later. The intake length L_1 and the baffle length L_3 of silencer for all models are same for some practical and manufacturing reasons.

Table 1. The geometries of various silencers (all lengths are in millimeters.)

Model No.	Baf. No.	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}	L_{11}	L_{12}	L_{13}	L_{14}	L_{15}	L_{16}	L_{17}
1	1	45	70	5	65	15	0	0	0	0	0	0	0	0	0	0	0	0
2	1	45	20	5	115	15	0	0	0	0	0	0	0	0	0	0	0	0
3	1	45	40	5	95	15	0	0	0	0	0	0	0	0	0	0	0	0
4	1	45	10	5	35	15	0	0	0	0	0	0	0	0	0	0	0	0
5	1	45	60	5	75	15	0	0	0	0	0	0	0	0	0	0	0	0
6	1	45	80	5	55	15	0	0	0	0	0	0	0	0	0	0	0	0
7	1	45	120	5	15	15	0	0	0	0	0	0	0	0	0	0	0	0
8	2	45	45	5	40	5	45	15	0	0	0	0	0	0	0	0	0	0
9	2	45	40	5	40	5	50	15	0	0	0	0	0	0	0	0	0	0
10	2	45	60	5	60	5	10	15	0	0	0	0	0	0	0	0	0	0
11	2	45	40	5	60	5	30	15	0	0	0	0	0	0	0	0	0	0
12	2	45	60	5	40	5	30	15	0	0	0	0	0	0	0	0	0	0
13	3	45	30	5	35	5	30	5	30	15	0	0	0	0	0	0	0	0
14	3	45	20	5	20	5	20	5	65	15	0	0	0	0	0	0	0	0
15	3	45	40	5	20	5	20	5	45	15	0	0	0	0	0	0	0	0
16	3	45	20	5	40	5	40	5	25	15	0	0	0	0	0	0	0	0
17	3	45	20	5	60	5	20	5	25	15	0	0	0	0	0	0	0	0
18	4	45	25	5	25	5	20	5	25	5	25	15	0	0	0	0	0	0
19	4	45	20	5	20	5	20	5	20	5	40	15	0	0	0	0	0	0
20	4	45	40	5	20	5	20	5	20	5	20	15	0	0	0	0	0	0
21	5	45	20	5	20	5	20	5	15	5	20	5	20	15	0	0	0	0
22	5	45	15	5	15	5	15	5	15	5	15	5	40	15	0	0	0	0
23	5	45	40	5	15	5	15	5	15	5	15	5	15	15	0	0	0	0
24	6	45	15	5	15	5	15	5	20	5	15	5	15	5	15	15	0	0
25	7	45	15	5	10	5	10	5	15	5	15	5	10	5	15	5	15	15

Figure 6 shows the STL for the silencers with one baffle and therefore with two chambers over a frequency range of up to 3000 Hz. In the lower frequency range up to 1180 Hz, the silencer with highest length for the first chamber, shows the maximum STL performance. Also, this is the same over the midrange frequencies up to 2200 Hz and over higher frequency range up to 3000 Hz.Figure 7 shows the STL for the silencers with two baffles and therefore with three chambers over a frequency range of up to 3000 Hz. Again, the effect of length of first chamber has been confirmed. It shows that the first chamber should have the highest length among the chambers.

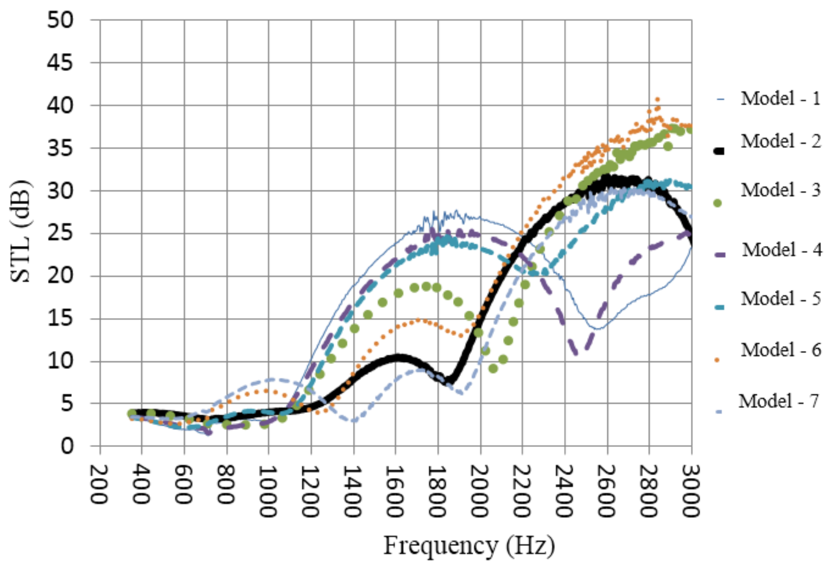

Figure 6. Comparison of experimental results for the models with two chambers

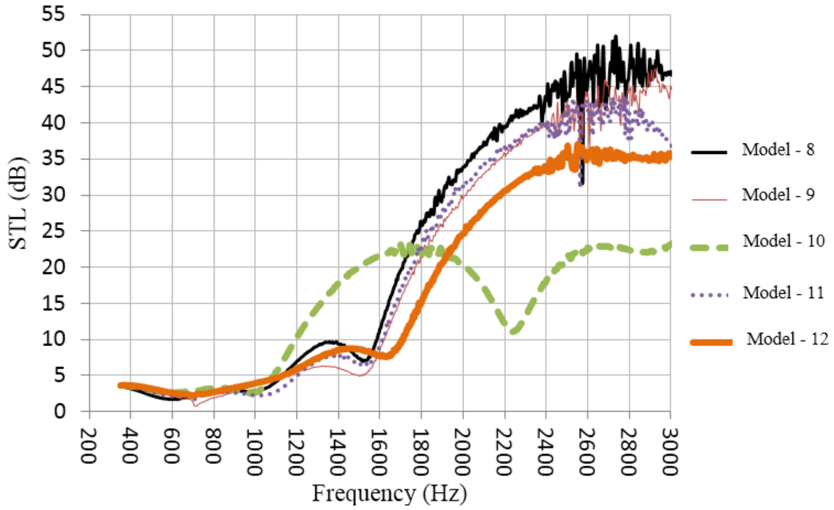

Figure 7. Comparison of experimental results for the models with three chambers

Figure 8 shows the STL results for the silencer with four chambers. In this case, the effect of length of the second chamber is more than others.

Figure 9 shows that for the silencer with five chambers, the model which has a higher length for its third chamber has a better performance for STL maximization in higher frequencies. Although, the performance of eighteen model is same others in lower frequencies but it is not well fit in midrange frequencies.

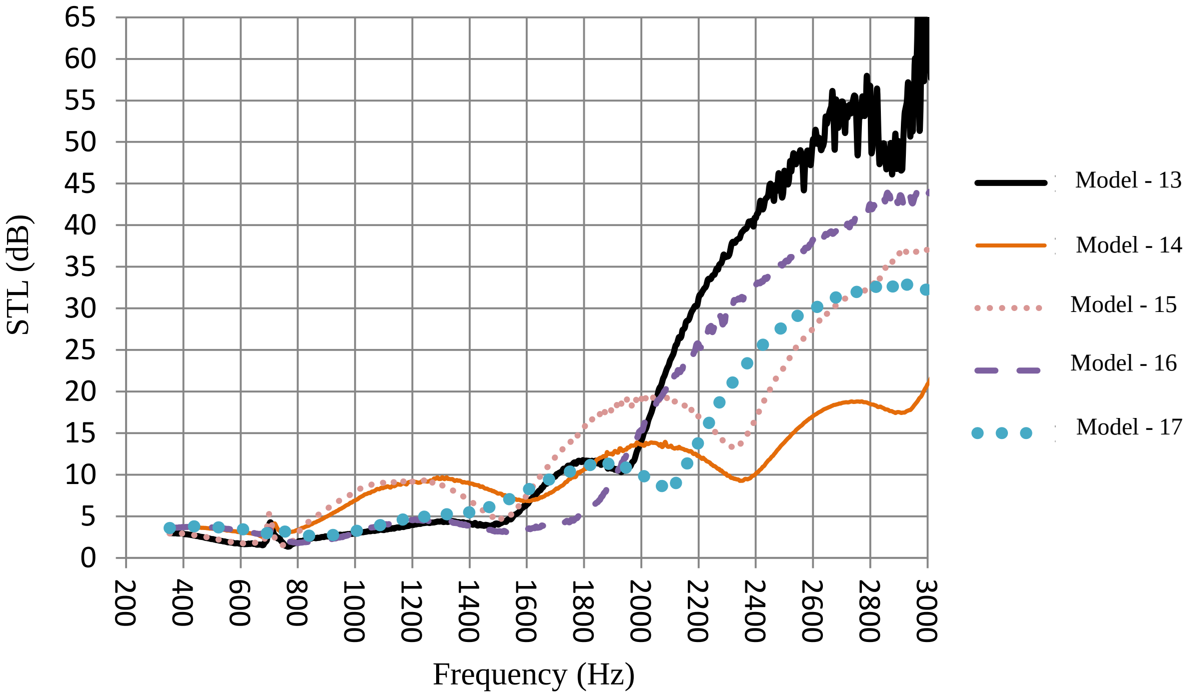

Figure 8. Comparison of experimental results for the model with four chambers

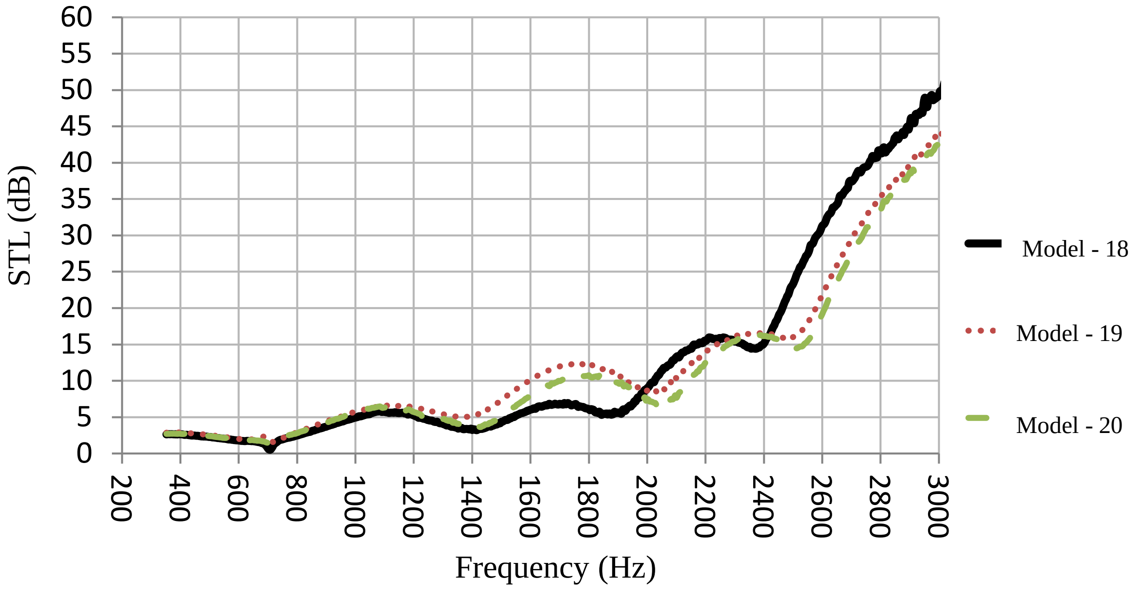

Figure 9. Comparison of experimental results for the model with five chambers

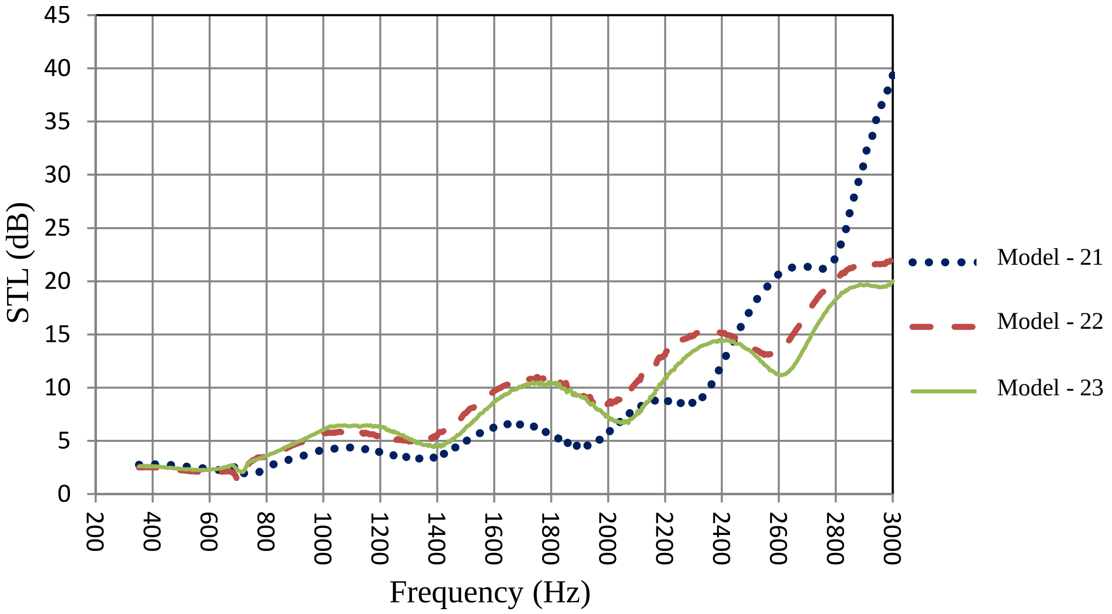

Figure 10. Comparison of experimental results for the model with six chambers

Figure 10 shows the STL performance for the models with six chambers. In low frequency range, a higher length for the first chamber is required. However, in the midrange frequencies, the chambers have a same length. In higher frequency range, the length of fourth chamber shall be less than others.

Figure 11 shows the STL performance for the silencer with seven chambers. Generally, its performance for maximization of STL is not comparable with others.

Moreover, figure 12 shows the STL performance for the silencer with eight chambers. Also, its performance for maximization of STL is not comparable with the rest of other models.

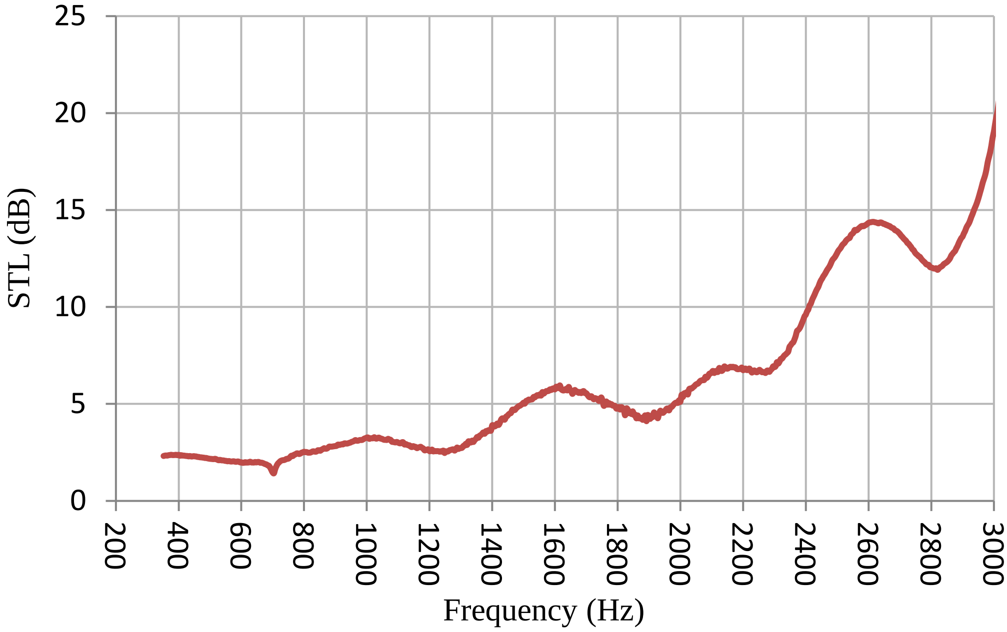

Figure 11. Comparison of experimental results for the Model 24 with seven chambers

In the frequency range of 1000-2000 Hz and in single-curtain models; It is observed that STL performance decreases as the curtain approaches the entrance and exit (2nd Model and 7th Model). The best performance is seen as the screen approaches the middle (Model 1). In two-fret models; It is seen that the STL performance decreases as the curtains approach the center (Model 12) to a large extent. As STL, the best performance curtains are they approach the exit (Model 10). In three-curtain models; As the curtains approach the center (Model 16), it is seen that the STL performance decreases. The best performance is seen as the curtains approach the entrance (Model 15). In four-curtain models; As the curtains approach the center (Model 18), it is seen that the STL performance decreases. The best performance is seen as the curtains approach the entrance (19th model). In five-curtain models; it is seen that RMS performance decreases when all curtain distances are equal (Model 21). The best performance is seen as the curtains approach the exit (Model 22).

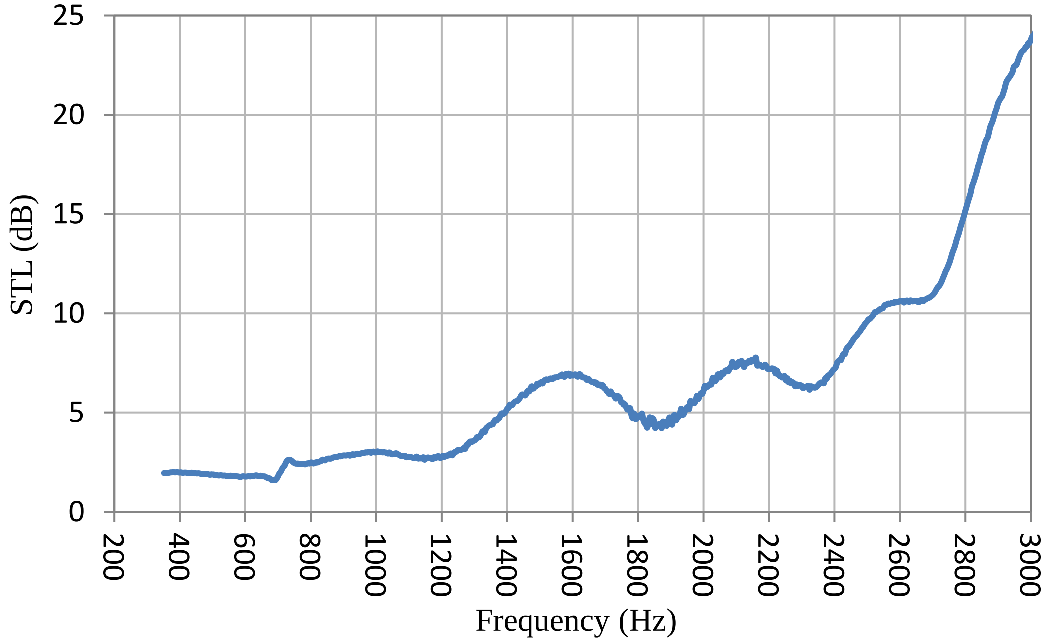

Figure 12. Comparison of experimental results for the Model-25 with eight chambers.

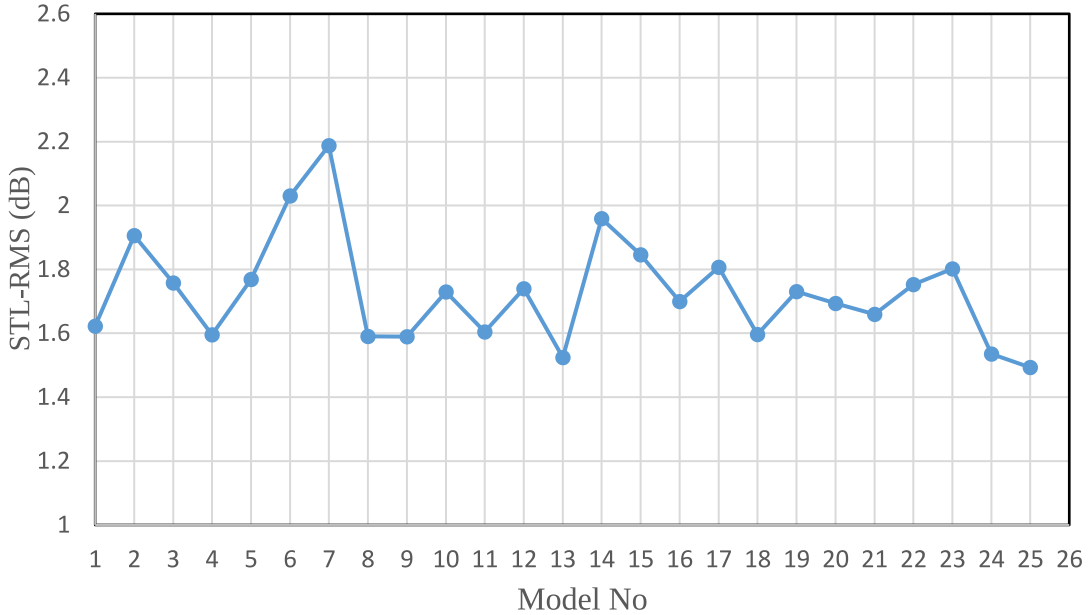

Figure 13. STL - RMS reduction of silencers models for 0-1000 Hz frequency range

In the frequency range of 2000-3000 Hz and in single-curtain models; As the screen approaches the middle (Model 1), it is seen that the RMS value gets worse. The best performance is seen as the curtains approach the exit (Model 6). In two-fret models; As the curtains approach the exit (Model 10), the RMS value deteriorates. The best performance is seen as the curtains approach the middle (Model 8). In three-curtain models; As the screen approaches the entrance (Model 14), it is seen that the RMS value gets worse. The best performance is seen as it approaches the center (13th Model). In four-curtain models; As the curtains approach the exit (Model 20), the RMS value deteriorates. The best performance is seen when the curtains approach the middle (Model 18). In five-curtain models; As the curtains approach the entrance (Model 23), the RMS value deteriorates. The best performance is observed when all curtain distances are equal (Model 21).

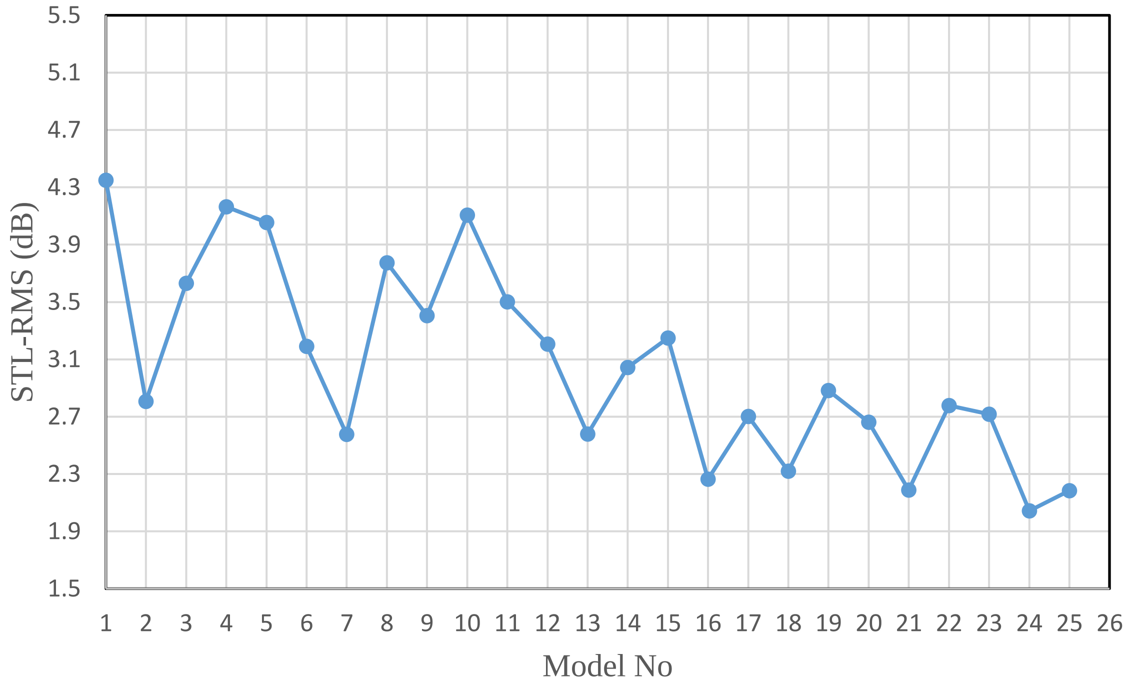

Figure 14. STL - RMS reduction values of silencers models for 1000Hz-2000 Hz frequency range

Figure 13 to 15 show the root mean square (RMS) of STL for different silencer models obtained as a result of experimental testing over the various frequency ranges. Each model is interpreted according to the number of baffle count groups for the frequency ranges between 0 - 1000 Hz, 1000 - 2000 Hz and 2000 - 3000 Hz. These figures represent the effect of number of chambers over each specific frequency range. It is confirmed that a silencer with two chambers is well enough to enjoy from the highest sound transmission loss over the frequency range of 0 to 3000 Hz. The numerical simulations are also performed to compare with the experimental results. The four-pole method or transfer matrix method is used for the numerical simulation. The results are shown in Table 2. At this regard, the RMS value of STL is calculated for the all of 25 experimental models. It is observed again that numerical and experimental evaluations are in good agreements.

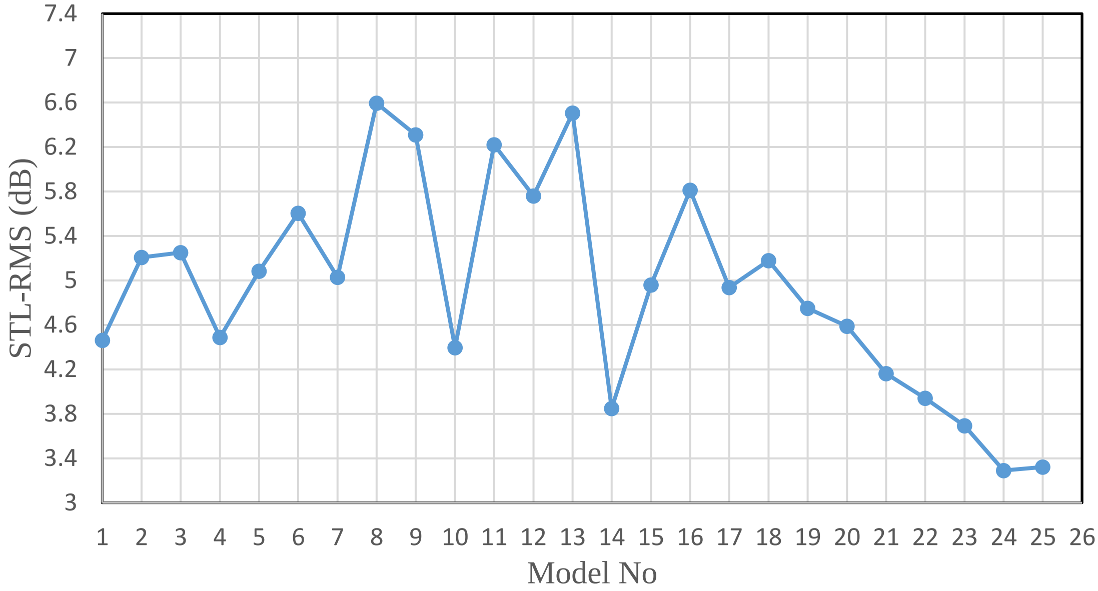

Figure 15. STL - RMS reduction of silencers models for 2000 Hz-3000 Hz frequency range.

Table 2. Comparison of STL - RMS values of silencers over the frequency range of 0-10000 Hz

Model Number	STL – RMS (dB)	
	Experimental	Numerical
1	5.7191	5.5656
2	5.4859	5.4000
3	5.4991	5.4477
4	5.5094	5.4675
5	5.6005	5.4640
6	5.6179	5.5399
7	5.6117	5.8008
8	6.3285	6.6758
9	5.9734	6.6235
10	6.5576	6.7770
11	6.2784	6.7420
12	6.0177	6.7137
13	6.7360	6.5547
14	5.9030	5.2010
15	5.9070	5.2151
16	5.9502	5.2265
17	5.9867	5.2126
18	6.5535	5.8347
19	6.4921	5.6967
20	6.3301	5.6816
21	6.9233	8.6141
22	7.3455	7.0333
23	7.3521	7.3217
24	7.3200	7.4461
25	7.2521	8.6141

Conclusion

In this paper, the theoretical and experimental evaluation of the acoustic performances of the reactive silencers were performed. The effect of number of chambers on the maximization of noise transmission loss was studied. It was confirmed that generally two chambers per each silencer is enough to meet the maximum sound transmission loss.

In future studies, more accurate results can be achieved with the joint solution of fluid dynamics and acoustic analysis of silencers.

Conflict of interest

The authors declare no conflict of interest.

References

[1] F. D. Denia, A. Selamet, M. J. Martínez, F. J. Fuenmayor, "Sound attenuation of a circular multi-chamber hybrid muffler", *Noise Control Engineering Journal*, vol. 56, no. 5, pp. 356-364, 2008.

[2] M.-C. Chiu, "Shape optimization of multi-chamber mufflers with plug-inlet tube on a venting process by genetic algorithms", *in Proc. of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, IDETC/CIE, 2009.

[3] M.-C. Chiu, "Simulated annealing optimization on multi-chamber mufflers hybridized with perforated plug-inlet under space constraints", *Archives of Acoustics*, vol. 34, no. 3, 305–343, 2009.

[4] Y.-C. Chang, "Shaped optimization of multi-chamber mufflers with open-ended perforated inlets using a simulated annealing method", *The Journal of the Acoustical Society of America*, vol. 127, no. 3, pp. 1800, 2010.

[5] Y.-C. Chang and M.-C. Chiu, "Optimization of Multi-Chamber Mufflers with Reverse-Flow Ducts by Algorithm of Simulated Annealing", *Archives of acoustics*, vol. 35, no. 1, pp. 13–33, 2010.

[6] S. Allam, "Numerical Assessment and Shape Optimization of Dissipative Muffler and Its Effect on I.C. Engine Acoustic Performance", *American Journal of Vehicle Design*, vol. 2, no. 1, pp. 22-31, 2014.

[7] G. W. Jang and M J. W. Lee, "Optimal partition layout of expansion chamber muffler with offset inlet/outlet", *International Journal of Automotive Technology*, vol. 16, no. 5, pp. 885–893, 2015.

[8] M.-C. Chiu, Y.-C. Chang, H.-C. Cheng, W.-T. Tai, "Shape Optimization of Mufflers Composed of Multiple Rectangular Fin-Shaped Chambers Using Differential Evolution Method", *Archives of Acoustics*, vol. 40, no. 3, pp. 311–319, 2015.

[9] M.-C. Chiu, "Numerical assessment of two-chamber mufflers hybridized with multiple parallel perforated plug tubes using simulated annealing method", *Journal of Low Frequency Noise, Vibration and Active Control*, vol. 36, no. 1, 3–26, 2017.

[10] L. Xiang, S. Zuoa, X. Wu, J. Liu, "Study of multi-chamber micro-perforated muffler with adjustable transmission loss", *Applied Acoustics*, vol. 122, pp. 35-40, 2017.

[11] M. Ranjbar, M. Nahid, A. Renawi, Z. Sadeqi, "Development of an Educational Noise Reduction Measurement Test Bench", *Journal of Robotic and Mechatronic Systems*, vol. 2, no. 1, pp. 27-32, 2017.

[12] M. Ranjbar, M. Alinaghi, "Effect of Liner Layer Properties on Noise Transmission Loss in Absorptive Mufflers", *Mathematical Modelling and Applications*, vol. 1, no. 2, pp. 46-54, 2016.

[13] M. Ranjbar, M. Kemani, "A Comparative Study on Design Optimization of Mufflers by Genetic Algorithm and Random Search Method", *Journal of Robotic and Mechatronic Systems*, vol. 1, no. 2, pp. 7-12, 2016.

[14] M. Ranjbar, B. Dalkılıç, E. Çalık, M. Cem Arslan, H. Arslan, "On Muffler Design for Transmitted Noise Reduction", *in Proc. of International Symposium on Multidisciplinary Studies and Innovative Technologies*, Gaziosmanpaşa University Tokat / Turkey November pp. 2-4, 2017.

[15] M. Ranjbar, M. Kermani, "Muffler Design by Noise Transmission Loss Maximization on Narrow Band Frequency Range", *in Proc. of the 7th Automotive Technologies Congress (OTEKON 2014)*, pp. 26-27 May, Bursa, Turkey, 2014.

[16] M. Ranjbar, M. Kermani, "On Maximization of Noise Transmission Loss in Mufflers by Geometry Modification Concept", *in Proc. of ASME District F - 2013 Early Career Technical Conference*, UAB, Birmingham, Alabama, November 2-3, 2013.

[17] A. Selamet, I. J. Lee, N.T. Huff, Acoustic attenuation of hybrid silencers, Journal of Sound and Vibration, vol. 262, pp. 509–527, 2003

[18] R. Guo, W. B Tang, W. W. Zhu, Comparison of 1D transfer matrix method and finite element method with tests for acoustic performance of multi-chamber perforated resonator, Applied Acoustics, vol. 112, pp. 140-146, 2016

[19] L. Xiang, S. Zuo, X. Wu, J. Liu, Study of multi-chamber micro-perforated muffler with adjustable transmission loss, Applied Acoustics vol. 122, pp. 35-40, 2017.

[20] H. Arslan, M. Ranjbar, E. Seçgin,,V. Çelik, "Theoretical and experimental investigation of acoustic performance of multi-chamber reactive silencers", Applied Acoustics, vol. 157, pp. 1-11, 2020

[21] M. L. Munjal, Acoustics of Ducts and Mufflers with Application to Exhaust and Ventilation System Design. 1st edition, John Wiley & Sons, 1987.