Muffler Design by Noise Transmission Loss Maximization

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ABSTRACT

The reduction of the emitted noise pollution from the exhaust system of engines is a real challenge for various industries. At this regard, mufflers have been used to reduce the transmitted noise from the engine of vehicles into the surrounding environment. Mufflers are designed to reflect the sound waves produced by the engine in such a way that they partially cancel themselves out. Noise transmission loss performance in muffler depends on its geometry. Therefore, maximization of noise transmission loss in mufflers using shape modification concept is an important research area.

In this research, three approaches have been followed for the maximization of noise transmission loss in mufflers by using of shape modification concept. To begin, Three-point method is used to calculate the transmission noise loss for a muffler. The effect of geometry of muffler on the maximization of noise transmission loss over the 1/3 octave band and the hole frequency range, are investigated. The same procedure is repeated by using of Transfer-Matrix Method for the calculation of noise transmission loss. The diameters and lengths of in-, out-takes and silencer are considered as the design variables. Finally, the optimum shape of muffler based on the considered design variables for having maximum noise transmission loss is searched by genetic algorithm method.

Keywords: Noise Transmission Loss, Geometry Modification Concept, Narrow Band Frequency, Design, Muffler, Silencer, Transfer Matrix Method, Genetic Algorithm.

ÖZ

Motorların eksoz sistemlerinden yayılan gürültü kirliliğinin azaltılması muhtelif endüstriler için gerçek bir sorundur. Bu bağlamda araç motorlarından çevreye yayılan gürültüyü azaltmak için susturucular kullanılmaktadır. Susturucular motordan gelen ses dalgalarını yansıtarak dalgaların birbirlerini kısmen yok edecek şekilde tasarlanırlar. Susturucudaki gürültü iletim kaybı performansı susturucunun geometrisine bağlıdır. Bu nedenle, şekil modifikasyonları konsepti ile susturuculardaki gürültü iletim kaybının maksimizasyonu önemli bir araştırma alanıdır.

Bu araştırmada şekil değiştirme konsepti kullanılarak susturuculardaki gürültü iletim kaybı maksimizasyonu için üç yaklaşım ortaya konulmuştur. Öncelikle, susturucudaki gürültü iletim kaybını hesaplamak için Üç-nokta metodu kullanıldı. Susturucu geometrisinin 1/3 oktav bandı üzerinde ve tüm frekans aralığındaki gürültü iletim kaybının maksimizasyonu üzerine olan etkisi araştırıldı. Ayni prosedür Transfer-Matris Metodu ile tekrarlanılarak gürültü iletim kayıpları hesaplandı. Susturucunun giriş-çıkış çap ve uzunluğu tasarım değişkenleri olarak kabul edildi. Son olarak, tasarım değişkenlerine göre maksimum gürültü iletim kaybı için, susturucunun optimum şekli ‘Genetik Algoritma Yöntemi’ ile araştırıldı.

Anahtar Kelimeler: Gürültü iletim kaybı, Geometri Modifikasyon Konsepti, Dar Bant, Frekans, Tasarım, susturucu, Matris Yöntemi, Genetik Algoritma

TO MY FAMILY

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I am most grateful to Prof. Dr. T. W. Wu and Dr. David Herrin from University of Kentucky for providing me with the MAP software of his unpublished versions and leading me when I had any questions. Last, but by no means least, I would like to thank Joyce MacNeg, who as a good friend, was always willing to help and give his best suggestions.

For any errors or inadequacies that may remain in this work, of course, the responsibility is entirely my own.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS/ ABBREVIATION

ANSI	American National Standards Institute
BEM	Boundary Element Method
dB	Decibel
EPFM	Exterior Penalty Function Method
FCB	Functional Cargo Block
FEM	Finite Element Method
FPM	Feasible Direction Method
GA	Genetic Algorithm
Hz	Hertz
IPFM	Interior Penalty Function Method
L_w	Sound Power Level in [watt]
LFN	Low Frequency Noise
M	Mach Number
MAP	Muffler Analysis Program
NR	Noise Reduction in [dB]
OSHA	Occupational Safety and Health Act
ref	Reference
RMSTL	Root Mean Square of Transmission Loss
SA	Simulated Annealing
TL	Transmission Loss in [dB]
TMM	Transfer Matrix Method

ρ	Density in [kg/m^3]
c	Sound Speed in [m/s]

Chapter 1

INTRODUCTION

Noise exists wherever people live specially in industrial cities because the life of human has knotted with machines and annoying noise has been produced while the engine of machine is working. The noise comes from the exhausters of jet engines, automobiles, funnels of powerhouses and so on. Four types of vehicle noise sources threaten the human hearing when they are inside. They are engine noise, wind noise, road noise and exhaust noise.

Generally, Noise Control Safety Standards come into play when the generation of noise cannot be avoided and must be addressed in some manner. Common solutions include the use of silencers or enclosures/cabins. Noise control is vital to protecting the safety of human/workers, as well as the comfort levels of those outside the workplace but still close enough to be affected.

Noise Safety Standards refers to many causes engaged in averting injuries or suffers resulting from the effects of sound. Whether by designing devices in a way as to decrease noise product, controlling that noise before it touches people, or through the use of personal protective equipment such as earmuffs, noise safety takes many forms, each created to meet the specific kinds of noise exist in an environment.

Noise Safety standards look for reducing the occurrence of negative effects of noise, coming from temporary distraction to short form of hearing loss, all the way through to continuous hearing loss or deafness.

While public environment is in endanger due to noise are producing by vehicles and this is an example of noise safety standards for productions are using in cities. Furthermore, these standards are not only using in determining where noise should be attenuated but also in guiding the process, from the initial measurement of noise , to the choices available to reduce it, their productivity, execution, and overall outcome of noise safety plans.

One of the main organizations of noise safety standards is Acoustical Society of America (ASA). Some other standards are OSHA and ANSI using to control noise.

At this regard, my study focuses on the reduction of exhaust noise and shakes which is produced by the muffler in automobile and other types of vehicles and industrial machines. Mufflers are widely used as the final section of any device which works with hot gas fluid or smoke. Either of this fluid is emitted to the natural or industrial environment by this exhauster. Totally, mufflers are in two types Reactive and absorptive. In this work, the design and maximization of noise transmission loss in reactive mufflers are discussed.

Nowadays, reduction of various existed noises is the significant issue for scholars in the area of Acoustics and vibrations to overcome. The main disadvantage of the noise is the corrupting influences of the shakes and vibrations of the noise. In this thesis, I have focused on the effective parameters on maximization of the TL to reduce the noise in the mufflers.

The thesis is arranged in five chapters: Introduction, Literature Review, Methodology, conclusion and results, and the reference section.

Following Chapter 1 is the introduction; a literature review is presented in Chapter 2. This literature review considers established findings. Chapter 3 represents the theories which are used in my study and considered the model to assess the TL values. Chapter 4 describes the orders of my attempts and test concentration to guarantee accuracy and repeatability of measurements. Furthermore, the obtained results are presented in chapter 4. These are the chapters which describe and verify my work according to the developed program and software that was used to investigate the performance of a simple multi section muffler. Chapter 5 includes final decision to the project and endorsements for the future work as well. And, the last chapter gives you the references which I benefited from them during my study. In the following that is an appendix section which contains the symbols were utilized during the work.

1.1 Definitions

1.1.1 Noise and Sound

The fluctuations in the air pressure in any media (like air) are appeared as an issue which is called noise and vibration and it is sensed by ear drum of the human that is called sound. The frequency ranges for healthy human hearing is from 20Hz to 20,000Hz. The term of ‘noise’ is used to show the unwanted sound.

1.1.2 Sound Wave

Variation of pressure which contains energy when it travels through different medium, it is called sound wave. These waves travel in the air by vibrating the molecules of air from source of sound.

1.1.3 Silencers

There is no technical difference between a muffler and silencer, and these two terms are utilized interchangeably. Although the terms might not be unknown for many people, mufflers make everyday life much more amiable. The demand of mufflers is mainly directed to the machine components or areas where there is a large amount of emitted sound such as exhaust tubes which has high pressure, gas turbines, and rotary pumps.

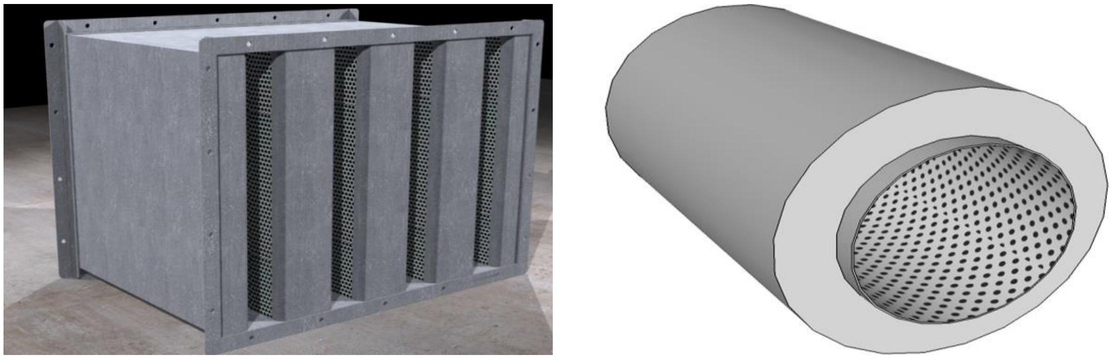
Although there are several demands for mufflers, they are really only two chief types which are used. They are absorptive and reactive silencers. Absorptive mufflers formed into corporation of sound absorbing materials to wrap the emitted energy in gas flow. Reactive silencers utilize a series of complicated paths to maximize sound attenuation while encountering set specifications such as dropping the pressure, volume flow, etc. Several of complicated silencers today combine both methods to optimize sound attenuation and prepare practical specifications.

1.1.4 Absorptive Silencer

An acoustic material is materials that decrease vibration and noise. There are four various types of material which are usually used to control, automotive noise and vibration. They are barriers and absorptions for noisy area and Isolation and damping in the vibrant area. Some materials control airborne noise and some of them control structure borne noise. In this area, each type of mentioned material has an impressible parameter on the sound transmission loss (TL).

This type of muffler is combined with the absorbing materials to transmute energy of acoustic into heat. Absorptive mufflers are mostly straight pipes which several layers of absorptive materials like fiberglass to decrease the emitted sound power. The attenuation property of the absorptive materials is constant and it is the significant feature of this type of the muffler. A dissipative muffler utilizes materials which absorb sound to remove the energy of the acoustic motion in the wave, as it emits through muffler.

More energy breaking and lower emitted sound power can be leaded by higher attenuation constants. One of the renowned applications of this type of muffler is in racecars where the engine performance is requested, and great back pressure is not produced to muffle the sound as well. This leads to advance the muffler performance. This type is goof in the applications which are involved in broadband and narrowband noises.



(a) (b)

Figure 1. (a)Duct absorptive muffler[1],(b) Circular silencer with absorptive outer [2]

1.1.5 Reactive Silencer

To decrease the amount of acoustic energy transmuted, another mufflers are used with a number of complicated paths. This is done by alteration in impedance at the junctions and makes ascent to reflected waves. Degradation the engines' performance is happened by minimizing the amount of energy transmuted, so the energy which back to the source is really high. This type of muffler is really well-known to use for combustion engines, and mufflers in rough environments. The performance of the muffler is efficient in low frequencies while the absorptive ones uses in high frequencies.

There is a difference between these two types of silencers; absorptive muffler breaks the energy of acoustic, while reactive one retains the energy and ruinous interference to reduce the emitted sound power. Reactive silencers, which are usually used in automotive applications, reflect the sound waves return towards the source and hinder sound from being transmitted along the pipe. The governed principal on designing the silencer is a Helmholtz resonator or expansion chamber, and needs line theory of acoustic transmission.

Three criteria describe the performances of mufflers and they are: Noise reduction, Insertion loss, and Transmission loss.


(a) (b)

Figure 2. (a) Automobile muffler [3], (b) Industrial muffler [4]

1.1.6 Transmission Loss (TL)

The difference between the sound power level of incident wave and the transmitted wave is defined as the TL.

1.1.7 Sound Power Level (L_w)

Sound power level is a positive amount of the quantity of acoustical energy cultivated by a sound source. It is not audible like sound pressure.

1.1.8 Sound Pressure Level (L_p Or SPL)

Human can make sense the sound pressure. The waves of sound are miniature oscillations of pressure around atmospheric pressure. The oscillations attack on the eardrum and sound is heard.

Chapter 2

LITERATURE SURVEY

A. Selamet et. al has investigated deeply on the effects of various amounts of length on the performances of acoustic diminution of expansion chambers which have common axis. In this study, three methods are put to use to conclude the transmission loss [5]. M. L. Munjal has derived four pole matrices for inlet and outlet chambers for small mean flow Mach number in a manner. He also showed that the behaviors of the normal inlets and outlets are relatively at the same as the extended both ones [6]. A better made technique has been presented by the T. W. Wu et. al. To obtain the four-pole parameters to utilize in the BEM is presented. This method only resolves the boundary element matrix once at any frequency [7].

Z. Tao et. al. are presented the theory of decomposition and power of transmission via the estimation of the plane wave are the approaches for assessing the transmission loss to conclude the incident power [8]. Renato Barbieri et. al. Has used the combination of analysis of finite element and the possible direction approach which is called Zoutendijk's for designing the shape of mufflers. The principle aim is to achieve the acoustic muffler's dimensions with maximization the transmission loss in the desired frequency ranges [6].

M. P. ŁUSZCZYŃSKA et. al. have studied the influence of low frequency noise(LFN) on the execution of the mental performance. In this case study, they have examined and exposed that the LFN which is occurring at normal levels in the industrial control rooms have the influences on the human mental function and personal contentment [10]. A. Luczak has represented the outcomes of an examination of harassment happened by low-frequency noise that took place at work stations [11].

S. Bilawchuk et. al. have tried to derive and utilize the three- point method for estimating TL were twofold concurrent estimations are taken to achieve the incident sound pressure level [12]. One of the features of the Functional Cargo Block (FCB) is an air filtration system which has two inlets; one on each side of the cabin, and have filters which eject particles of dust from the atmosphere of the module. This module is called Zarya control module. Noise produced by the system of air filtration, increased the feasible constant noise of acoustic's specification in the octave band ranges from 205 Hz to 8000 Hz. To overcome this case, F. W. Grosveld et. al. have provided a practical noise reduction mechanism [13].

S. N. Y. Gerges et. al. have worked on the transfer matrix method (TMM) for prophesying the TL of a muffler in lower frequency ranges where the frequency of the engine’s fires happens. In the study, only fixed and concentrated mufflers are taking an account [14]. The muffler's room volume in a system of noise control is limited to practical operations and repairing. So, increasing the function of muffler makes so essential.

L. J. Yeh et. al. have done their study by genetic algorithm (GA) and simulated annealing (SA) at the same time. Finally, it had revealed that the GA had more precise results [15]. S. H. Seo et. al. have suggested a new design approach that improves efficiency the organization of resonators while staying the bulk minimized [16]. J. Li et. al. have worked on the development method which follows the Four-Pole elements by the use of Boundary element method (BEM) which is suitable for estimating TL in the systems of acoustic silencer [17]. Y. C. Chang et. al. have worked on the process of optimization. In their work, they have tried to use Neural Network and the dimensions of muffler as the data were going to use for input data. The output of its work was achieved by their mathematical model. Cooperation of the Genetic Algorithm and Neural Network could be found in their job to catch an optimal shape of a muffler [18]. M. C. Chiu et al. have operated on the theory of the four pole matrix in a muffler with single chamber. It means a chamber with side inlet and outlet pipe. To reduce the noises, GA and Gradient Method have been used. A mathematic gradient method which was utilized in this research was included interior penalty function method (IPFM), exterior penalty function method (EPFM) and feasible direction method (FDM). The outcomes of this work were efficient parameter for designing the muffler with high Sound Transmission Loss [19]. Four-pole matrix has been used to analyze and increase the acoustical features performance of a muffler numerically in the range of small space. Again, GA has been applied by M. C. Chiu to the separated numerical method to derive sound transmission loss and find the optimum shape [20].

W. Bing et. al. have made a model of muffler and analyze the inner sound issue, compare the FEM and transmission matrix approaches and then estimate TL [21]. A reactive muffler has been built by P. Bhattacharya et. al. and the outcomes which were estimated at 1200 rpm have been compared with the three frequent types of muffler. They were brake thermal efficiency, brake specific fuel, and drip of pressure [22]. A. Gagorowski et. al. Have also worked on the several points which have an influence on the modeling the shape of the muffler and cause to reduce the acoustic noise sent out from the vehicles. The aim of their work was to remove the frequency bands of acoustic waves in the course of the spent gases which are expelled from the engines. They are fatal to the health of the human [23].

H. Abdullah et. al. have presented a numeric analysis of TL for the exit pipe of the muffler by utilizing an approach of transfer matrix. In this case study, they have tried to expand a written program to prophesy the TL of muffler [24].

After careful consideration of the previous works, it is realized that maximization of the transmitted noise loss in mufflers is still an ongoing research area. Therefore, the scope of this thesis is to assess the factors which have influences on maximization of Transmission Loss (TL) of mufflers as used in any vehicles or machines which they need to emit burned mixed gases from combustion engines. For the sake of achieving this goal, the focus had fixed on the Acoustical Parameters to optimize the shape of common shape of the muffler. Pressure, length of inlet, outlet pipes, silencer’s length, and diameter of different sections of the muffler were considered. To achieve my aim, I have studied on my issue by using the three-point method and four-pole method as well as do survey on the results of the three-point method and four-pole method by using Genetic Algorithm (GA) as an optimization method to find the optimum value of the TL with the influenced parameters. To apply these operations, I have considered one of the examples of the MAP software in all my process and just some modifications have been took into account to find the several results for more comparisons.

The outcome of this work is identification to perform a study on parameters in design of mufflers and geometry modification to achieve the maximization of the transmission loss (TL).

In the following, the concepts of this study will be discussed in theory and result chapters. Also, the calculation of TL for various geometries of mufflers are investigated and reported. Later, the geometry of muffler is optimized by genetic algorithm method to find the best optimum shape of muffler which gives maximized noise transmission loss.

Chapter 3

THEORY AND METHODOLOGY

Generally, two methods have been widely used by researchers for the calculation of noise transmission loss in muffler. They are transfer matrix method and three-point method.

3.1 Calculation of Noise Transmission Loss by Transfer Matrix Method

3.1.1 Plane Wave Propagation

For propagating the plane wave in a straight tube with length of L, constant cross section S, and the velocity of the mean flow *V* (figure 3), the sound pressure *p* and the volume velocity *v* anywhere in the tube element can be shown as the summation of left and right traveling waves. Neglecting the impacts of higher order modes is the cause of validation of the plane wave propagation. Utilizing the impedance analogy, the sound pressure *p* and volume constancy v at locations 1(upstream end) and 2 (downstream end) in Fig. 1 ($x=0$ and $x=L$, in order) can be stated by:

$$p_1 = Ap_2 + Bv_2 \tag{3.1}$$

and

$$v_1 = Cp_2 + Dv_2 \tag{3.2}$$

Where A, B, C, and D are usually called the four-pole constants. They are frequency-dependent complex values manifesting the acoustical characteristics of the tube (Pierce, 1981) [25].

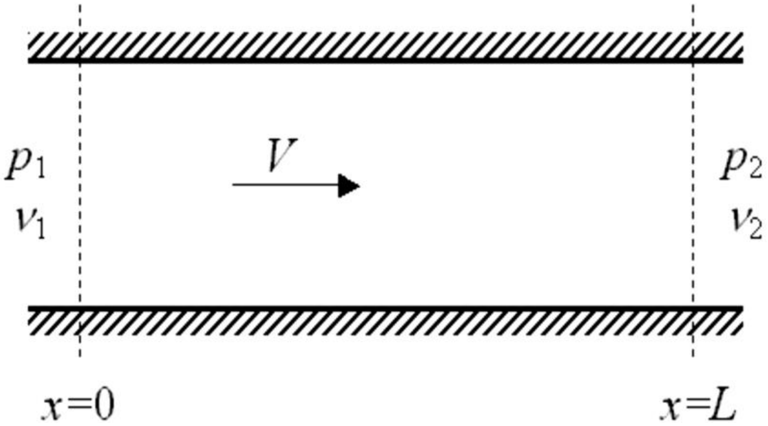


Figure 3. Plane wave propagation in a rigid straight tube transporting a turbulent incompressible mean flow

The four-pole constants for non-viscous medium are:

$$A = \exp(-jMk_cL)\cos k_cL \tag{3.3}$$

$$B = j(\rho c/S)\exp(-jMk_cL)\sin k_cL \tag{3.4}$$

$$C = j(S/\rho c)\exp(-jMk_cL)\sin k_cL \tag{3.5}$$

$$D = \exp(-jMk_cL)\cos k_cL \tag{3.6}$$

Where M=V/c is the Mach number of mean flow which is less than 0.2, c is the sound speed (m/s), $k_c$is the thermally conductive wavenumber(rad/m) ($k_c = k/(1-M^2)$), k is the acoustic wavenumber (rad/m) ($k = \omega/c$), ω is the angular frequency (rad/s), ρ is the fluid density (kg/m^3), and j is the square root of -1. In Eqs. (3) to (6), by substituting the quantity of M=0 for stationary Medium [14].

3.1.2 Transfer-Matrix Method

In this method, the matrix will be shown is using for a simple duct (Fig. 3). If the number of ducts increases, so the final matrix will be the separated production of each connected muffler to each other.

The equations (1) and (2) can be written in the way of matrix form as

$$q_1 = T_1 q_2 \tag{3.7}$$

Where $q_i = [p_i \ v_i]^T$ is a vector of thermally conductive state variables (i=1, 2) and [8]

$$T_1 = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{3.8}$$

The regarded approach computes the TL of muffler by using transfer matrix approach [26, 27, and 28]. A linear acoustic 4 pole transfer matrix:

$$\begin{bmatrix} p_1(x) \\ v_1(x) \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} p_2(x) \\ -v_2(x) \end{bmatrix} \tag{3.9}$$

Where the p_1 and v_1 are the pressure of sound and velocity of normal particle at the inlet, respectively. Aslo, p_2 and v_2 are similar values at the outlet. There is negative sign on v_2 is added because the vector at the outlet on the BEM model is against the normal vector at the inlet. To obtain the matrix, imagine a simple rectangular duct with (v_1, p_1) and (v_2, p_2) parameters as inlet and outlet one. The governed pressure equation is:

$$p(x) = A\cos kx + B\sin kx \tag{3.10}$$

By taking derivation this equation with respect to location (x), we have:

$$\frac{dp}{dx} = -kA\sin kx + kB\cos kx \tag{3.11}$$

And the equation of velocity is:

$$v(x) = \frac{i}{\rho\omega}\frac{dp}{dx} = \frac{i}{\rho c}(-A\sin kx + B\cos kx) \tag{3.12}$$

With considering the existed boundary conditions on the equations of the pressure and velocity respectively, you will find the unknown parameters. The existed boundary conditions are:

At the entrance of inlet$(x = 0)$, there are $v_1$and p_1 as well as at the end of the outlet$(x = l)$, there are v_2 and p_2 . Finally, the matrix of simple duct will be derived:

$$\begin{bmatrix} p_1(x) \\ v_1(x) \end{bmatrix} = \begin{bmatrix} \cos kl & i\rho c \sin kl \\ \frac{i}{\rho c} \sin kl & \cos kl \end{bmatrix} \begin{bmatrix} p_2(x) \\ -v_2(x) \end{bmatrix} \tag{3.13}$$

In the above sentence, the coefficients matrix is called Four-pole transfer matrix and is shown by [T] for a straight duct. In practice, it is more convenient to use volume velocity instead of the particle velocity v in [T]:

$$\begin{bmatrix} p_1 \\ s_1 u_1 \end{bmatrix} = \begin{bmatrix} \cos kl & \frac{i\rho c}{s_2} \sin kl \\ \frac{i s_1}{\rho c} \sin kl & \frac{s_1}{s_2} \cos kl \end{bmatrix} \begin{bmatrix} p_2 \\ s_2 u_2 \end{bmatrix} \tag{3.14}$$

Where $s_1 v_1$ and $s_2 v_2$ are volume velocity at inlet and outlet, respectively.

Compared to the three-point method, the four-pole method is actually a much slower method for computing the TL; this is because of three-point method’s single BEM run nature. However, the four-pole matrix is not produced by the three-point method. The significant features of the muffler can be shown by the four-pole matrix, and also can be joined with other four-pole matrices when the muffler is linked to other components in the exhaust system [29].

3.2 Octave Band Frequency Range

The data which are obtained from sound pressure, sound power and sound intensity are given in terms of 1/3 octave band levels. Also, transmission loss data is usually represented in terms of 1/3 octave band.

Table 1. Center, lower, and upper frequencies for standard set of octave and 1/3 octave bands covering the audible frequency range

Octave band			**1/3 octave band**		
Lower Frequency f_1(Hz)	**Center Frequency f_0(Hz)**	**Upper Frequency f_2(Hz)**	**Lower Frequency f_1(Hz)**	**Center Frequency f_0(Hz)**	**Upper Frequency f_2(Hz)**
22	31.5	44	22.4	25	28.2
			28.2	31.5	35.5
			35.5	40	44.7
44	63	88	44.7	50	56.2
			56.2	63	70.8
			70.8	80	89.1
88	125	177	89.1	100	112
			112	125	141
			141	160	178
177	250	355	178	200	224
			224	250	282
			282	315	355
355	500	710	355	400	447
			447	500	562
			562	630	708
710	1000	1420	708	800	891
			891	1000	1122
			1122	1250	1413

Generation laws for octave and third octave bands are under several frequency equations.

3.3 Calculation of Noise Transmission Loss by Three-Point Method

Another approach to calculate the transmission loss is three-point method. It is the commonplace method to calculate the TL. In this way, TL values are completely relying on the locations of the considered pressures. In details, two techniques there are. The existed difference is because of the technique of the derivation of these equations. These equations will be categorized in approach one and two, and the approach one is the common method to compute the TL in this method. [24, 30] Approach one is followed below:

$$p_{1=} p_i e^{ikx_1} + p_r e^{-ikx_1} \tag{3.15}$$

$$p_{2=} p_i e^{ikx_2} + p_r e^{-ikx_2} \tag{3.16}$$

Where p_i represents the incoming/incident wave, and p_r represents the reflected/transmitted waves. From Eq. (15) and (16), values of p_i and p_r are obtainable. The right solution for p_i is

$$p_i = \frac{1}{2i\ \sin[k(x_1 - x_2)]}\left(p_1 e^{-ikx_2} - p_2 e^{-ikx_1}\right) \tag{3.17}$$

Here, in this equation, it is necessary that the $\sin[k(x_1 - x_2)] \neq 0$

The transmission loss (TL) is expressed as the difference between the levels of the arriving sound level and departing sound level.

$$TL = 10\ \log_{10}\frac{W_i}{W_o} \tag{3.18}$$

Where $W_i$is the arriving sound power and W_o is the departing sound power. Since the power of sound is proportional to the square of sound pressure amplitude as well as the area of tube, Eq.(18) turns into:

$$TL = 20\log_{10}\frac{|p_i|}{|p_3|} + 10\log\frac{A_i}{A_o} \tag{3.19}$$

Where A_i and A_o are the areas of the inlet and outlet tubes, respectively. If $A_i = A_o$, Eq. (19) reduces to

$$TL = 20\log\frac{|p_i|}{|p_3|} \tag{3.20}$$

Where the wave number k in [m^{-1}] is

$$k = {}^{2\pi f}/_{c} \tag{3.21}$$

$\omega =$ Is the normal circular frequency in [rad/s]

Figure 4 shows the location of the three measurement points. Also, the incident P_i , reflected P_r , and transmitted P_t , are the pressure waves.

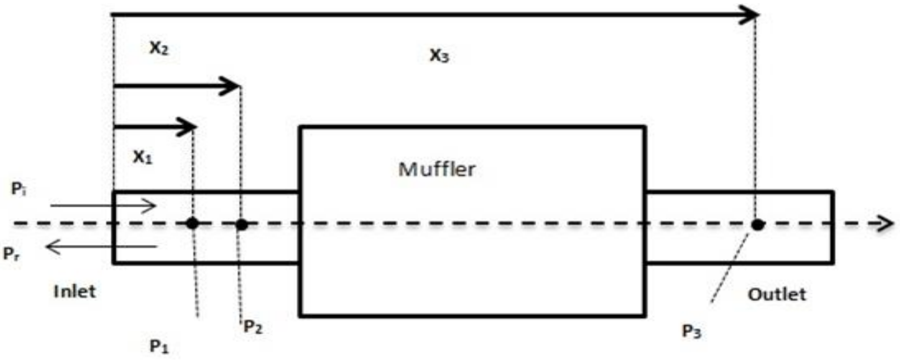


Figure 4. The Three-Point Method

3.4 Genetic Algorithm Method (GA)

A condensed description about Genetic Algorithms method is available in Charbonneau 03, and the right reference about him is mentioned in reference section as well. Hypothesize that there is a group of design parameters **v** and a model that explains the parameters **v** to measure a function $F(\nu)$ for a specific design. Now, a set of variable which maximizes the function has to be found by the optimization algorithm. The GA works as follows: at first, initialize the population fortuitously and estimate the fitness of its members, reproduce chosen members of present population to harvest offspring population, substitute present population by offspring population, estimate fitness of novel population members and reiterate until the most appropriated member of the present population is supposed suitable enough.

The general procedures of this method starts with defining a counter (K=K+1). Secondly, set a population of l chromosomes (ϑ^l). Thirdly, compute the objective function amounts of l chromosomes (F^l). Fourth step is to produce novel chromosomes by implementing competence scaling to the chromosomes, and rejoining fit parent encryptings. Fifth is deleting elements of the population to make more space for the new generations. Sixth step is estimating each novel chromosome as in step 3, and enter it into the population. Seventhly, if the ceasing criterion has been satisfied, cease and return the chromosome with the best competence, otherwise keep on with step 4 [31].

3.5 TL Maximization Procedure

There are several optimization algorithms methods which concentrate on typical types of optimization tasks. Some algorithms are suitable for constrained problems, while on the contrary some of them are useful for unconstrained optimizations. Some approaches demand the objective function and the constraints to create linear functions of design variables, and other can carry out nonlinear objective functions and restrictions. One can also discern between local optimization algorithms, which may captured in a local extremum, which always find the global extremum.

Optimization is explained as the minimization and maximization of an object function to restrict on its variables [Nocedal 99, Marburg 02a]. In this fact, the optimization problem is defined as follows [31]

$$F(d_1, d_2, d_3, L_1, L_2, L_3) = RMSL(d_1, d_2, d_3, L_1, L_2, L_3) \rightarrow max. \qquad (3.22)$$

$$RMSTL = \sqrt{\frac{\int_{f_{min}}^{f_{max}} TL^2(f)df}{f_{max}-f_{min}}}\ dB \tag{3.23}$$

Where d_1, d_2, d_3 are the diameters and l_1, l_2, l_3 are the lengths of intake, silencer, and the outtake respectively. They are shown in figure 5

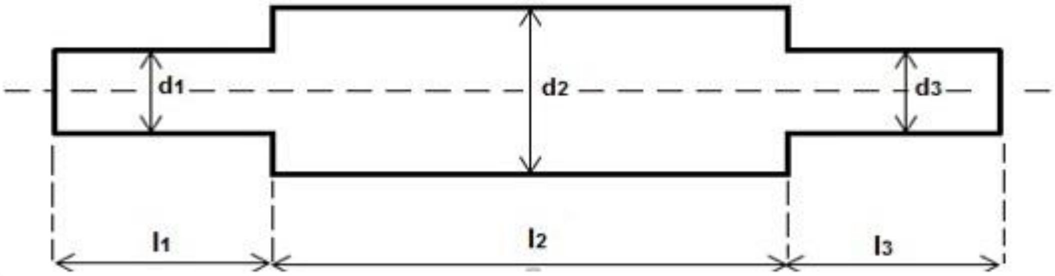


Figure 5. schematic shape of muffler related to the RMSTL

The Eq. (24) shows the considered constrains on the design variables. All values are defined in inches, such as:

$$1 \leq l_1, l_2, l_3, d_1, d_2, d_3 \leq 19.5 \tag{3.24}$$

While all design variables have an interval in they are between a min and max desired values, thus min and value of this design are 1 inch and 19.5 inches respectively. The equations (22, 24) show us that the design space of the defined problem is 6-dimensional problem. The aim is to decide the values of l_1, l_2, l_3, d_1, d_2 and d_3 which maximizes the objective function [32].

In this research, the Genetic Algorithm (GA) method is considered to find the best optimum value of a simple muffler which generates a maximum RMSTL. In the following, a short description of GA method is presented.

Chapter 4

RESULTS

4.1 Muffler Model Description

The considered model is shown in figure 5, is the three-chamber muffler. The gas from the engine comes into the muffler, and the output of muffler is the gas banished from muffler to the atmosphere [32].

4.2 TL Calculation by the Three-Point Method

I have used this method in two phases; in the first phase, a simple chamber muffler has been considered which contains inlet and outlet pipes with a same diameters and a silencer as you can see in the fig. 1.

A study is done by the results from the MAP [33] software. MAP is written by T. Wu in university of Kentucky to calculate the TL for various muffler shapes using BEM.

In figures 6, the TL calculated by the MAP is presented. Here, a bulk is considered and the pressures were chosen arbitrarily. The inlet and outlet radiuses are 6 inches, i.e. R1=R2, and the coordinate of point 1 is selected as zero (X1=0). Furthermore, point 2 has X2=3 inches, and point 3 is 29.99 inches from inlet area (X3= 29.99).

In figure 6, the logarithmic measure of TL calculated by MAP is shown.

It is shown in figure 6 that the maximum TL is about 48 dB in the frequency of 2000 Hz.

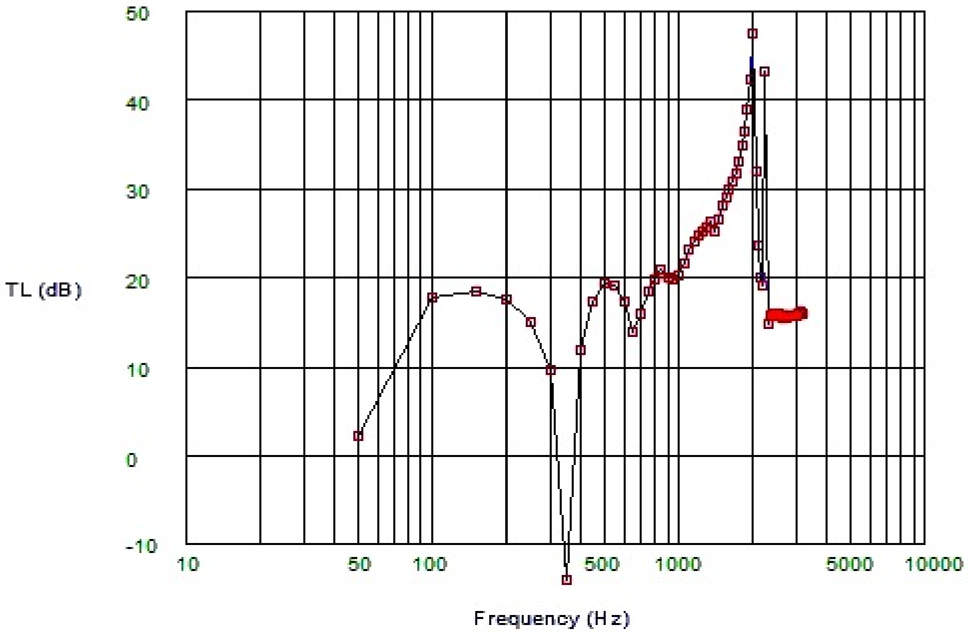


Figure 6. TL result from MAP software

There are some differences between the results calculated by our self-written code and the MAP software, see figures 6. In following, some clarifications in this context are presented.

The three-point method is based on considering position of three points. MAP has two options as settings for considering three points' positions. In fact, differences will be appeared in auto adjustment which whether would consider two points while one of them is zero completely, or evaluating the points according to other types of equations. Consequently, by thinking over the zero amounts, it shows us that positions of points are not important enough for calculation of TL by MAP. Although in Manual setting, that would be possible to change the positions of points by user, but the desired result is not shown.

In MAP, when the considered fluid is Air, it ignores the sound velocity, while if it is utilized Refrigerant, the sound velocity will be scored. The speed of sound has significant influence on increasing the amount of TL in some parts.

4.3 Calculation of TL in the Range of 1/3 Octave Band By the Three-Point Method

The three-point method [23] is used to measure the muffler TL. This method considers two points on the input and one point on the output tube of a muffler. The location of these points is considered from the left edge of inlet tube of muffler.

The impulse of inlet tube is done by velocity or pressure, while termination of anechoic is utilized at the outlet end [24]. Furthermore, as an analysis tool for the calculation of the noise TL in muffler, the MAP software [33] is used. By doing the experiments in different sections of the muffler, it was understood that the inlet and outlet tubes have more influences on the TL. So, the previous program has developed on these two sections in the range of one-third octave band, and all situations that can be existed have been considered.

Several various methods are available by MAP software for the calculation TL in mufflers. As indicated, the three-point method is considered for the calculation of noise TL in this study.

The effect of cross-sectional radius of muffler parts has been considered to be investigated in a narrow band frequency range, namely 200 Hz one third octave band. This frequency range includes the area between 178 to 224 Hz. This frequency range is interesting for practical design applications of muffler in the real world.

The size of inlet tube and outlet tube is increased in each step for 0.5 inch from the original size up to maximum size of silencer cross sectional radius. Also, the reverse procedure is followed for silencer. It means that the experiments were done with reducing of silencer radius from its maximum radius for 0.5 inch in each step until when its radius reaches to the radius of inlet/outlet pipes.

The geometry of considered model for the muffler is shown in Fig. 8. It is a muffler with simple expansion chamber. As it is shown below, different sections of muffler contains Inlet, Ex-tube 1, Silencer (which it has soundproof of Polyester around the silencer with fixed thickness, and inner interface tube between ex-tube 1 and 2, with in-flange and out-flange at the both sides of the silencer), Ex-tube 2, and the outlet. The radiuses of inlet, silencer and outlet tubes are considered as r_1, r_2, and $r_3$respectively (Fig. 8).

As more information about the considered model of muffler is that the thickness of the soundproof is 0.5 inch [33].

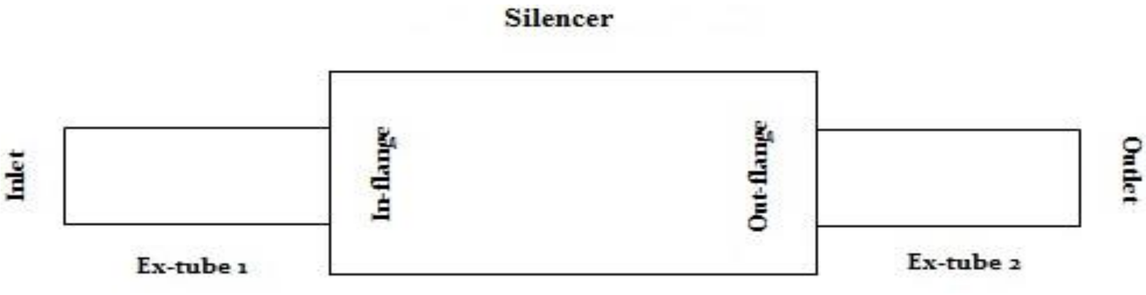


Figure 7. Schematic shape of considered muffler

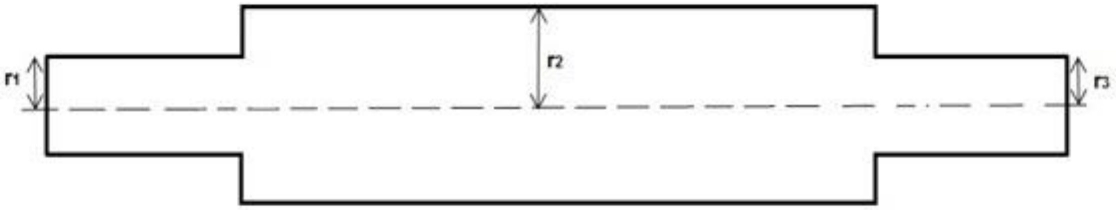


Figure 8. Schematic shape of muffler with mentioned parameters

The original radius of inlet is 1 inch. Then, it is being increased by 0.5 inch up to 3.5 inches in five steps, see table 2.

Table 2. Original size of muffler parts and the steps of changing in the inlet radius

Section position	**Original radius (inch)**	**Modified radius of inlet (inch)**				
		1st attempt	**2nd attempt**	**3rd attempt**	**4th attempt**	**5th attempt**
Inlet	1	1.5	2	2.5	3	3.5
Silencer	3.5	3.5	3.5	3.5	3.5	3.5
Outlet	1	1	1	1	1	1

In this experiment, the Three-point method is applied to complete my experiment with several variants that are mentioned in the methodology section. The frequency range for value of the TL is between 177 Hz to 250 Hz. Five steps considered for each concept (0.5 inches increment for each step).

Minimum obtained value for TL is assigned to the radius of silencer. This is shown by MAP below:

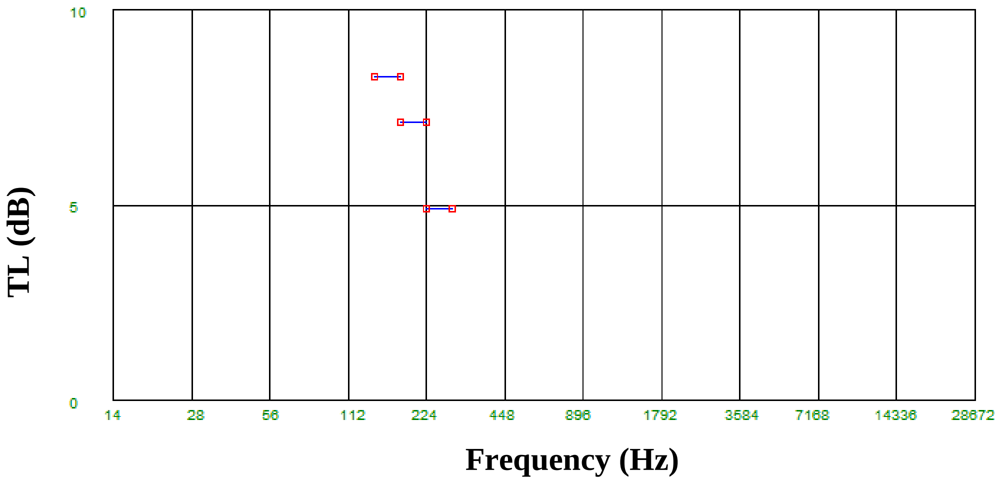


Figure 9. TL value when the outer radius of silencer changed to 1.5 inches (4th attempt).

Table 3. TL amounts while the radius of silencer is changed from 3-1.5 inches

Frequency range (Hz)	**Original TL of the Muffler (dB)**	**Modified Muffler**			
		Attempt 1	**Attempt 2**	**Attempt 3**	**Attempt 4**
149-186	18	14.6	12	9.8	8.7
186-224	17.2	13.9	11	8.8	7.7
224-261	15.9	12.7	9	6.7	4.9

As the table 3 shows us, it is understandable that the reduction of silencer which is related to outtake of silencer causes to decrease the TL value over the frequency range of 170-250 Hz.

Also, maximum obtained value for TL is assigned to the inlet tube. This is shown by MAP below:

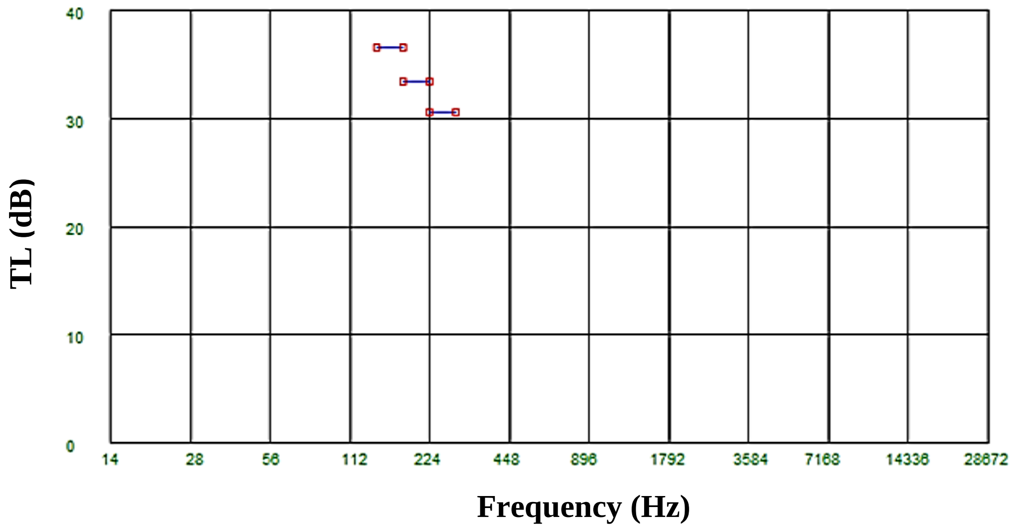


Figure 10. TL value when the inlet radius is changed to 3 inches (4th attempt).

Table 4. TL amounts for inlet tube in considered frequency ranges

Frequency range (Hz)	**Original TL of the Muffler (dB)**	**Modified Muffler**				
		Attempt 1	**Attempt 2**	**Attempt 3**	**Attempt 4**	**Attempt 5**
149-186	18	14.7	21.1	31	36.5	28.5
186-224	17.2	14.7	21	30.5	33	26.5
224-261	15.9	14.5	20	29	30.5	25

By comparing the results which are shown in table 4, it is understandable that the increment of the inlet radius leads to increase the TL value over the frequency range of 170-250 Hz. In spite of existing a drop is seen at attempt 5, but the TL values in that attempt is beyond of the original TL.

During this study, the all considered sections for this experiment instead of outlet area have their own effects on increasing the TL amount, but they are not as much as the impact of intake area. In fact, reduction in the area's dimensions of mentioned sections except inlet area cause to increase the TL amount in this narrow band frequency.

Another achieved point in this section was the neutral effect of silencer. The increased amounts of TL were not much to be taken into account. Below tables and graphs show this demand.

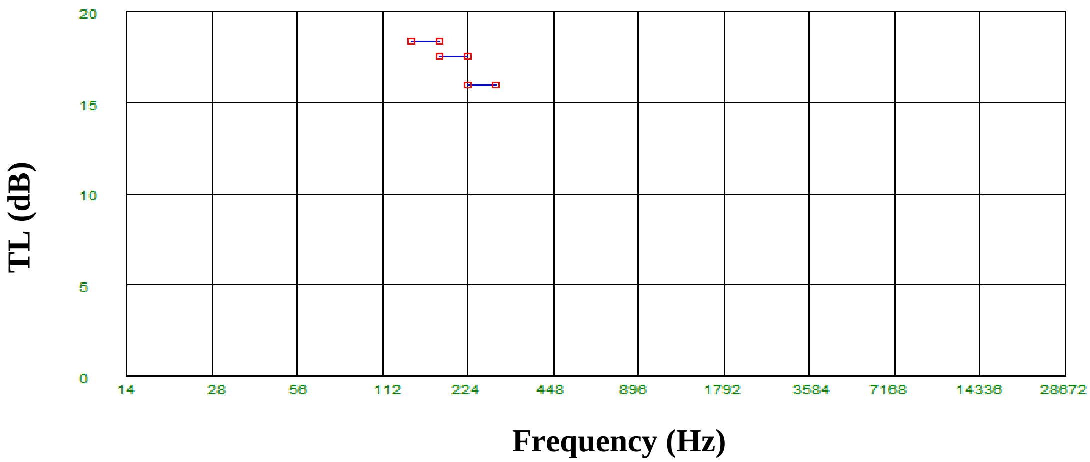


Figure 11. TL value when the radius of silencer changed to 3 inches (1st attempt).

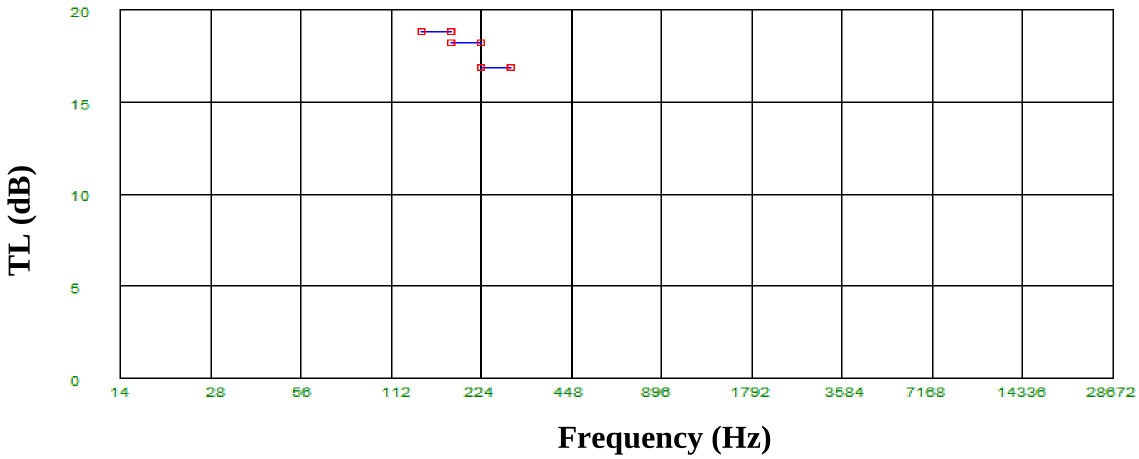


Figure 12. TL value when the outer radius of silencer changed to 1.5 inches (4th attempt)

Table 5. TL amounts while the radius of silencer is changed from 3-1.5 inches

Frequency range (Hz)	Original TL of the muffler (dB)	Modified muffler			
		Attempt 1	**Attempt 2**	**Attempt 3**	**Attempt 4**
149-186	18	18.5	18.7	18.9	19
186-224	17.2	18	18.2	18.4	18.5
224-261	15.9	16.3	16.6	16.8	16.5

4.4 TL Calculation with Transfer-Matrix Method (TMM)

In a real muffler, several elements connected together such as expansions, sudden contractions, extended tubes and/or perforated tubes are connected together in series. Each element is described by one transfer matrix, which depends on its geometry and conditions of flow. Therefore, it is essential to model each element and then to relate all of them to get the overall acoustic properties of the muffler. The final transfer matrix is the production of the individual system matrices.

To use up this method, the effects of lengths and areas were considered on the trend values of TL. These had been considered as the sensitivity options to find out the prominent factor for maximization of simple and commonplace muffler. To follow up the hypothesis, the amounts of length and radius of inlet, silencer, and outlet were put in trials respectively. They were done by length and radius incremental from 10% to 30 % of original values, and also, reduction from 10% to 30% from original value, as well. Below figures show you the effects of each factor on the trend of TL values and TL values over the wide frequency ranges.

These changes are distributed through six cases which contain increments and reductions. Then the figures are shown. For the case 1:

Table 6. Effects of inlet length variations on the TL amounts

	L_1 (inch)	**L_2 (inch)**	**L_3 (inch)**	**d_1 (inch)**	**d_2 (inch)**	**d_3 (inch)**	**TL (dB)**	**RMSTL (dB)**
-30%	4.5	18	6	1	3.5	1	53.4857	44.6563
-20%	5	18	6	1	3.5	1	52.6358	43.8113
-10%	5.5	18	6	1	3.5	1	51.8782	43.0522
Original	6	18	6	1	3.5	1	51.1977	42.3747
+10%	6.5	18	6	1	3.5	1	50.5825	41.7563
+20%	7	18	6	1	3.5	1	50.0233	41.1933
+30%	7.5	18	6	1	3.5	1	49.5127	40.6719

As the table 6, and figures 13 to 15 are showing, the TL has an inverse behavior through incremental trend of the inlet length. So, length reduction of inlet is sufficient for the maximization of TL.

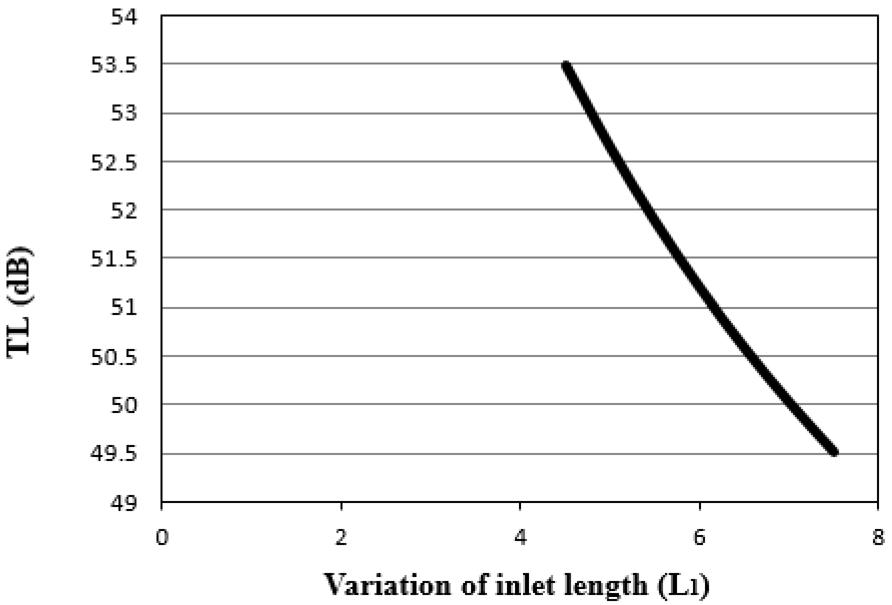


Figure 13. Variation of TL with respect to length of inlet

Also, TL amount over the wide frequency range is between 0-3000 (Hz):

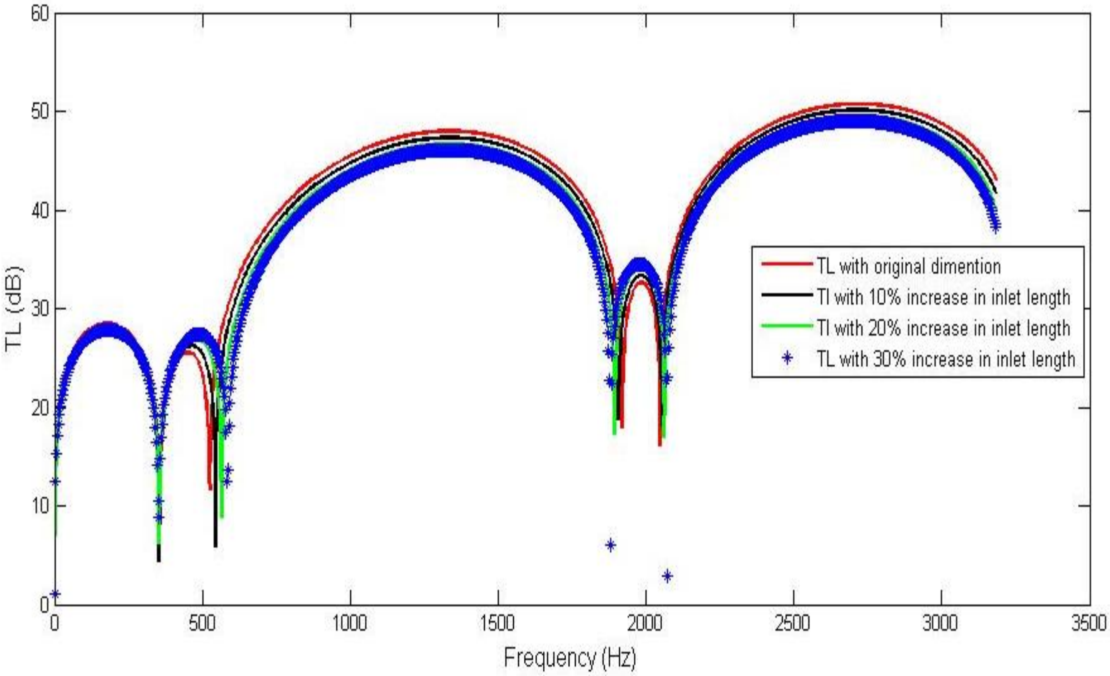


Figure 14. Noise transmission loss for increasing inlet geometry

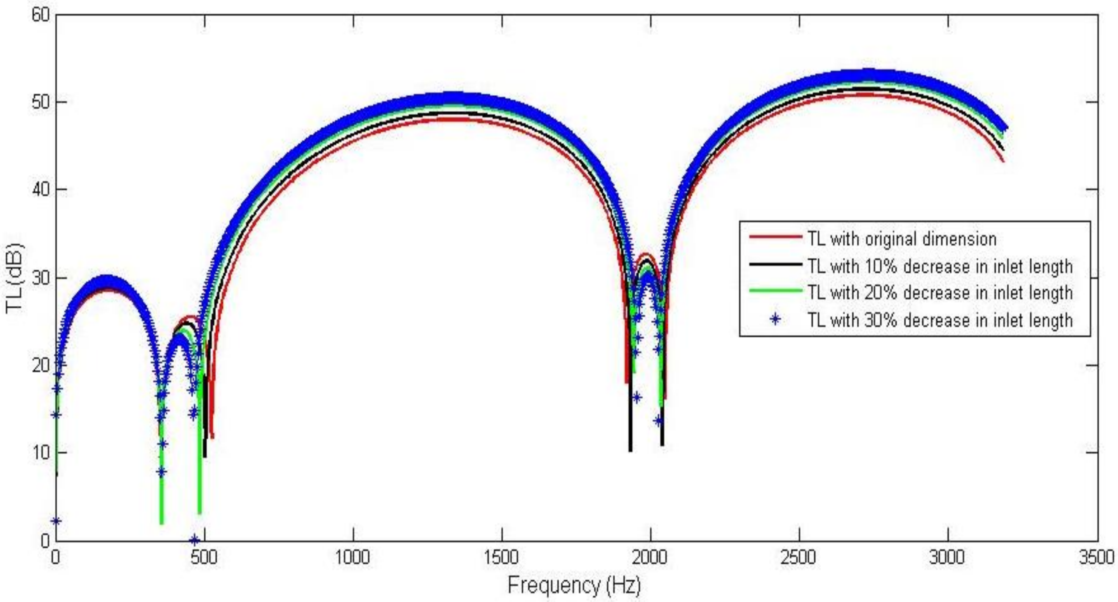


Figure 15. Noise transmission loss for decreasing inlet geometry

And for case 2, it is focused on the effects of silencer length:

Table 7. Effects of silencer length variations on the TL amounts

	L_1 (inch)	**L_2 (inch)**	**L_3 (inch)**	**d_1 (inch)**	**d_2 (inch)**	**d_3 (inch)**	**TL (dB)**	**RMSTL (dB)**
-30%	6	16.5	6	1	3.5	1	49.7704	41.0834
-20%	6	17	6	1	3.5	1	50.2586	41.5243
-10%	6	17.5	6	1	3.5	1	50.7341	41.9499
Original	6	18	6	1	3.5	1	51.1977	42.3747
+10%	6	18.5	6	1	3.5	1	51.6499	42.7878
+20%	6	19	6	1	3.5	1	52.0912	43.1921
+30%	6	19.5	6	1	3.5	1	52.5220	43.5879

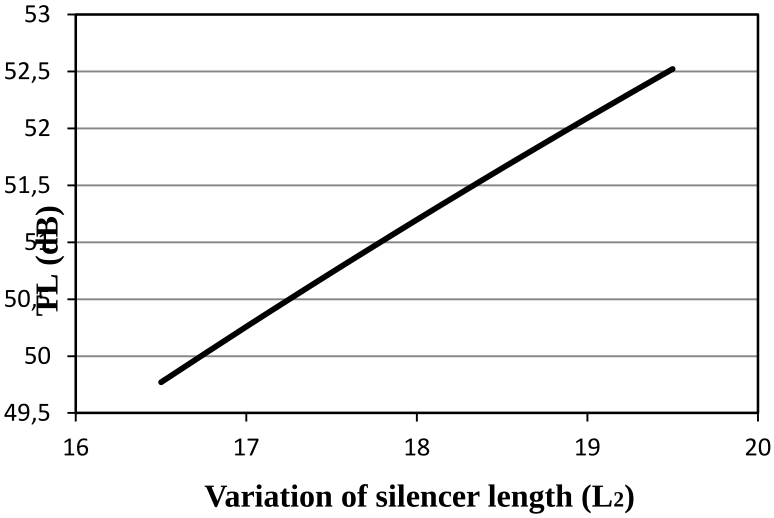


Figure 16. Variation of TL with respect to length of silencer

In this case, as the table 7 and figure 16 are presenting, the TL values get direct influences by increasing/decreasing the length of silencer. However, increasing the length of silencer is the profitable factor for maximization of the TL in mufflers. Figures 17 and 18 demonstrate the trend of TL according to the length of silencer.

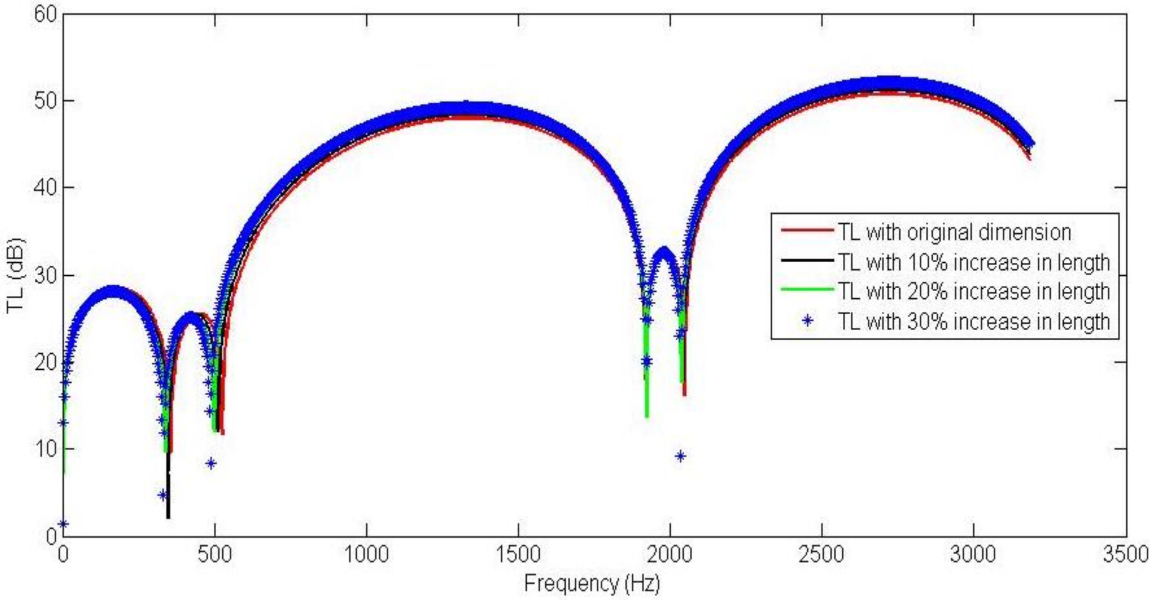


Figure 17. Noise transmission loss for increasing silencer geometry

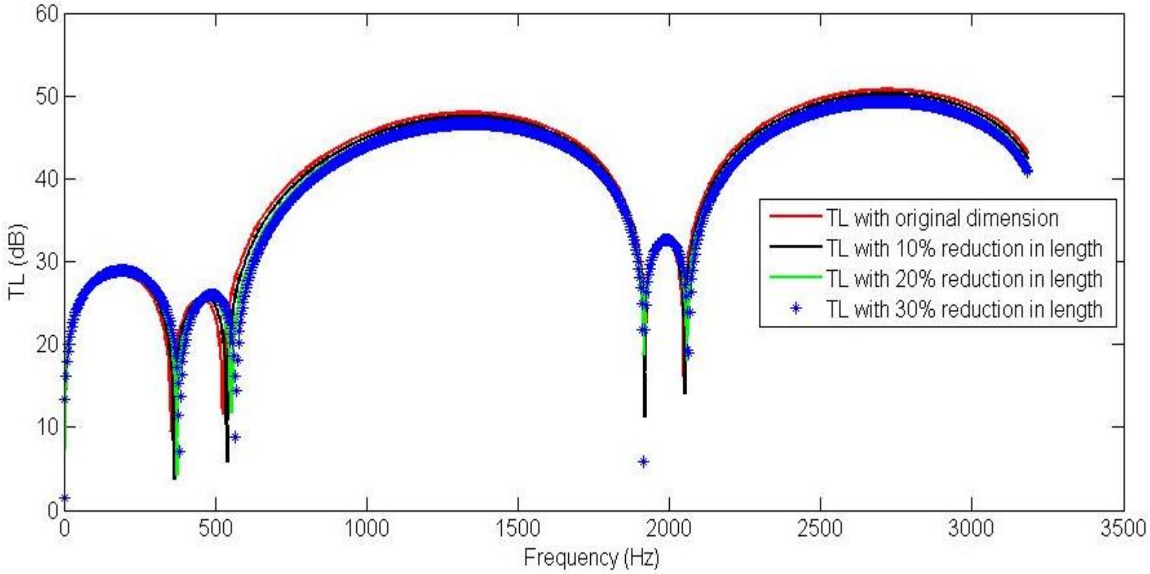


Figure 18. Noise transmission loss for decreasing silencer geometry

And for case 3, it is focused on the effects of silencer length:

Table 8. Effects of silencer length variations on the TL amounts

	L_1 (inch)	**L_2 (inch)**	**L_3 (inch)**	**d_1 (inch)**	**d_2 (inch)**	**d_3 (inch)**	**TL (dB)**	**RMSTL (dB)**
-30%	6	18	4.5	1	3.5	1	56.1819	46.9538
-20%	6	18	5	1	3.5	1	54.3572	45.2571
-10%	6	18	5.5	1	3.5	1	52.7058	43.7381
Original	6	18	6	1	3.5	1	51.1977	42.3747
+10%	6	18	6.5	1	3.5	1	49.8098	41.1336
+20%	6	18	7	1	3.5	1	48.5242	40.0076
+30%	6	18	7.5	1	3.5	1	47.3269	38.9746

As the table 9 and figure 19 are showing us that the behavior of the outlet length is similar to the inlet length. Therefore, both of them have the inverse effects on the TL values. Then, reduction of the outlet length is an efficient factor in maximization of the TL, as the figures 20 and 21 are presenting.

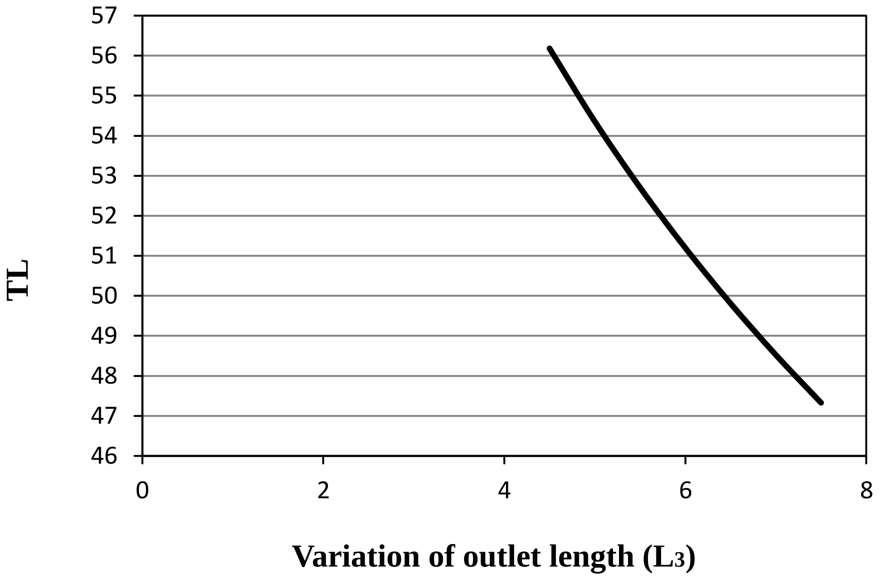


Figure 19. Variation of TL with respect to length of outlet

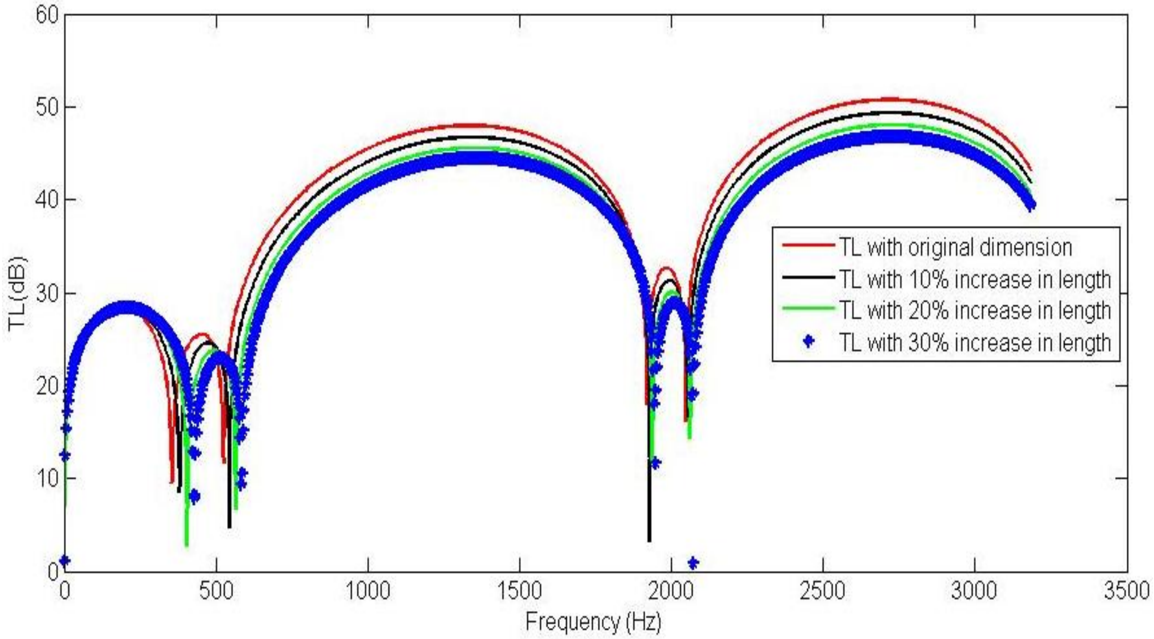


Figure 20. Noise transmission loss for increasing outlet geometry

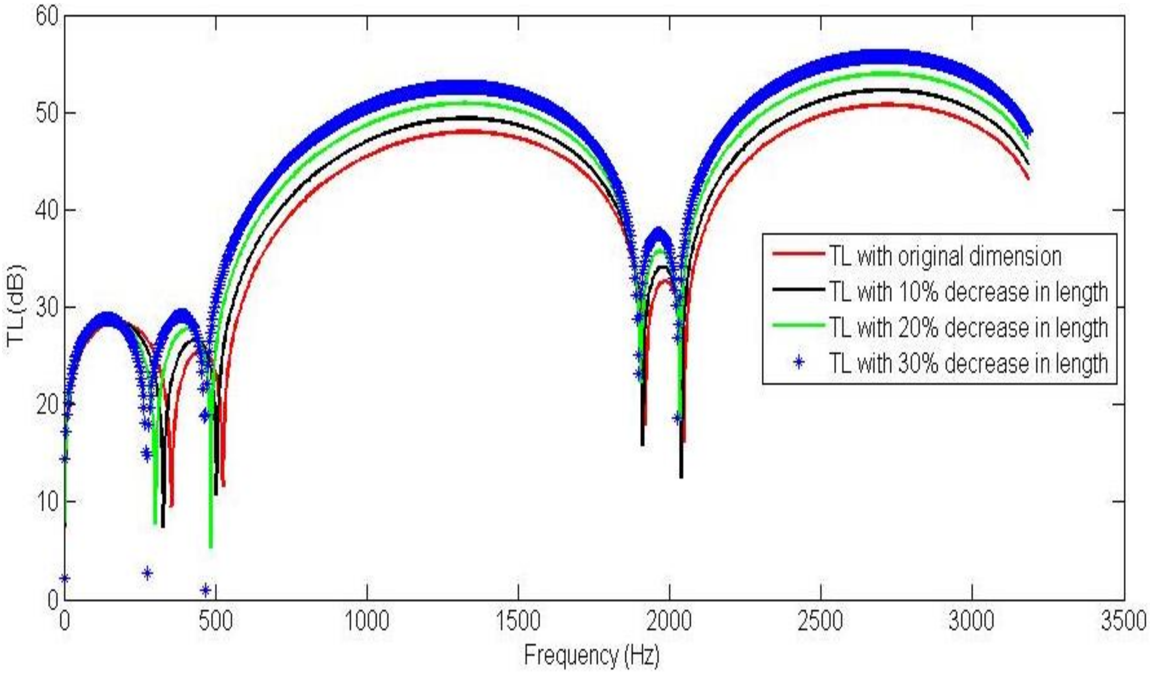


Figure 21. Noise transmission loss for decreasing outlet geometry

And for case 4, it is focused on the effects of inlet diameter:

Table 9. Effects of inlet diameter variations on the TL amounts

	L_1 (inch)	**L_2 (inch)**	**L_3 (inch)**	**d_1 (inch)**	**d_2 (inch)**	**d_3 (inch)**	**TL (dB)**	**RMSTL (dB)**
-30%	6	18	6	0.7	3.5	1	53.5747	42.7475
-20%	6	18	6	0.8	3.5	1	53.0723	42.8337
-10%	6	18	6	0.9	3.5	1	52.2837	42.7389
Original	6	18	6	1	3.5	1	51.1977	42.3747
+10%	6	18	6	1.5	3.5	1	53.3066	41.8898
+20%	6	18	6	2	3.5	1	53.0912	42.3051
+30%	6	18	6	2.5	3.5	1	52.8235	41.7027

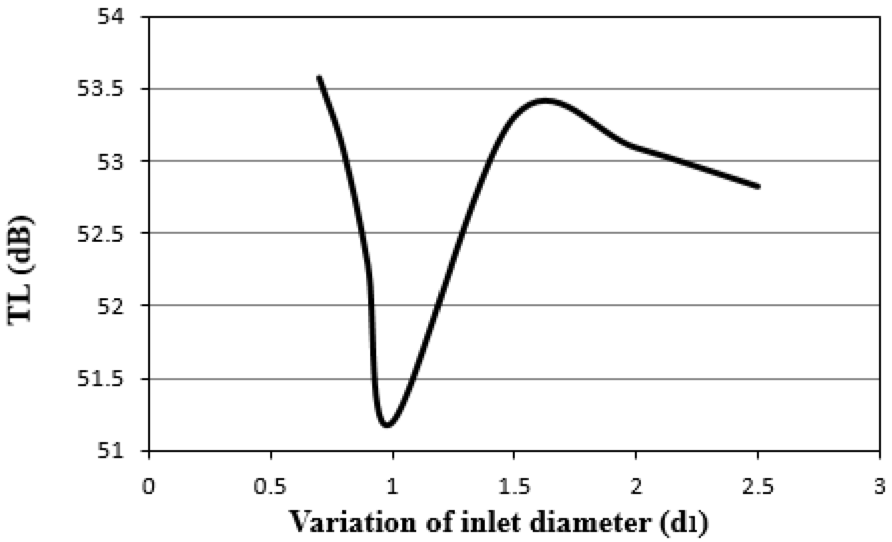


Figure 22. Variation of TL with respect to diameter of inlet

Figure 22 and table 10 are relating that the diameter of inlet is not a reliable factor due to its fluctuations of TL amounts along the increments and reductions of the inlet diameter. This is clear enough as the figures 23 and 24 are showing.

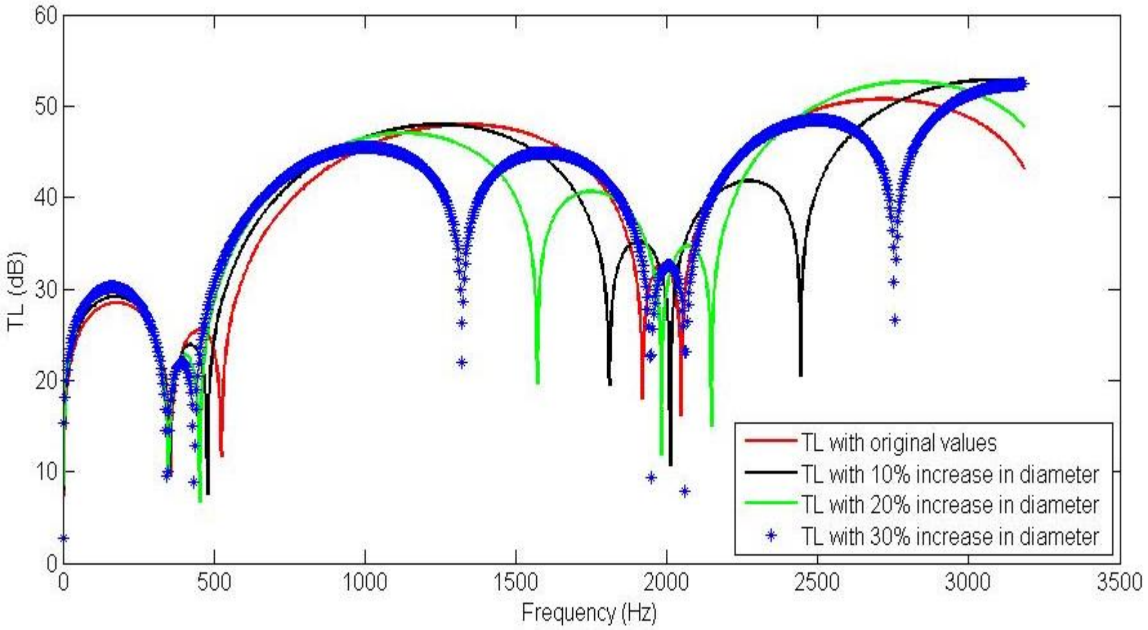


Figure 23. Noise transmission loss for increasing inlet geometry

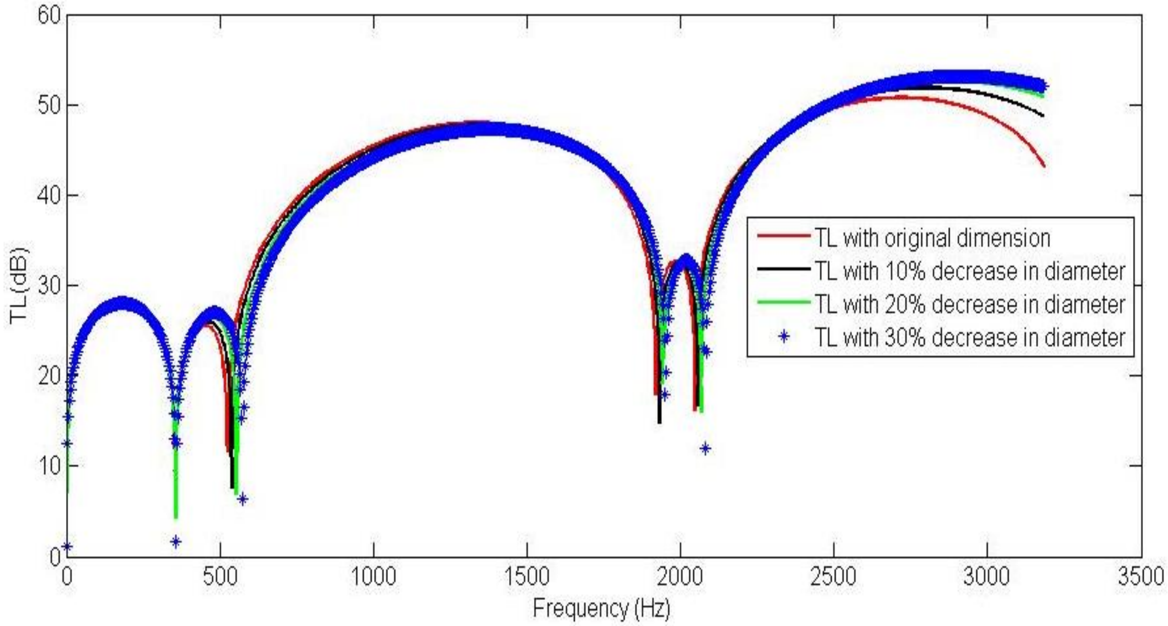


Figure 24. Noise transmission loss for decreasing inlet geometry

In the case 5, it is focused on the effects of silencer diameter:

Table 10. Effects of silencer diameter variations on the TL amounts

	L_1 (inch)	**L_2 (inch)**	**L_3 (inch)**	**d_1 (inch)**	**d_2 (inch)**	**d_3 (inch)**	**TL (dB)**	**RMSTL (dB)**
-30%	6	18	6	1	2	1	51.7066	42.4440
-20%	6	18	6	1	2.5	1	50.7220	41.2180
-10%	6	18	6	1	3	1	49.5870	41.7885
Original	6	18	6	1	3.5	1	51.1977	42.3747
+10%	6	18	6	1	4	1	51.9869	42.1634
+20%	6	18	6	1	4.5	1	52.1780	41.5127
+30%	6	18	6	1	5	1	52.0379	41.7382

Similarly to inlet diameter, table 11 and figure 25 show that the silencer diameter has the same behavior through increasing/reduction of diameter. However, the reduction has the safe trend and may cause the maximization of TL. Figure 26 has shown more fluctuations rather to figure 27 which contains the reduction trends of silencer diameter. Therefore, reduction can be a reliable factor for this aim.

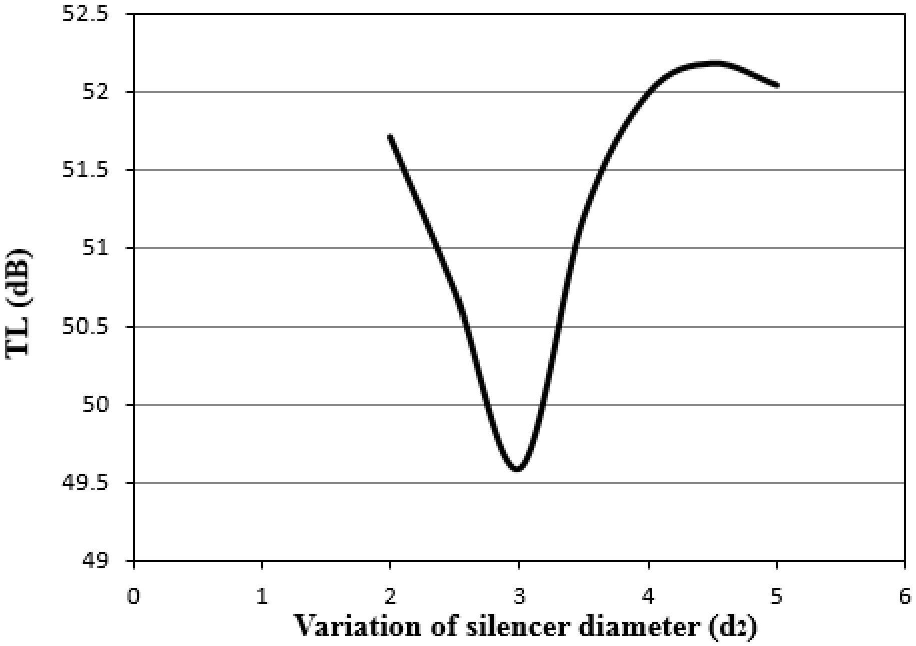


Figure 25. Variation of TL with respect to diameter of silencer

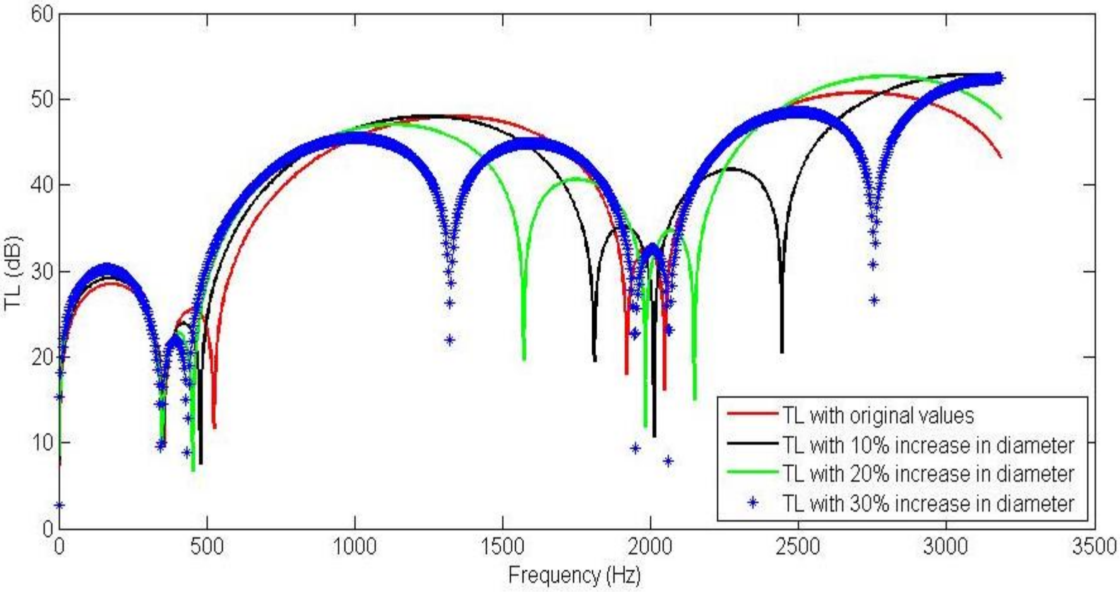


Figure 26. Noise transmission loss for increasing silencer geometry

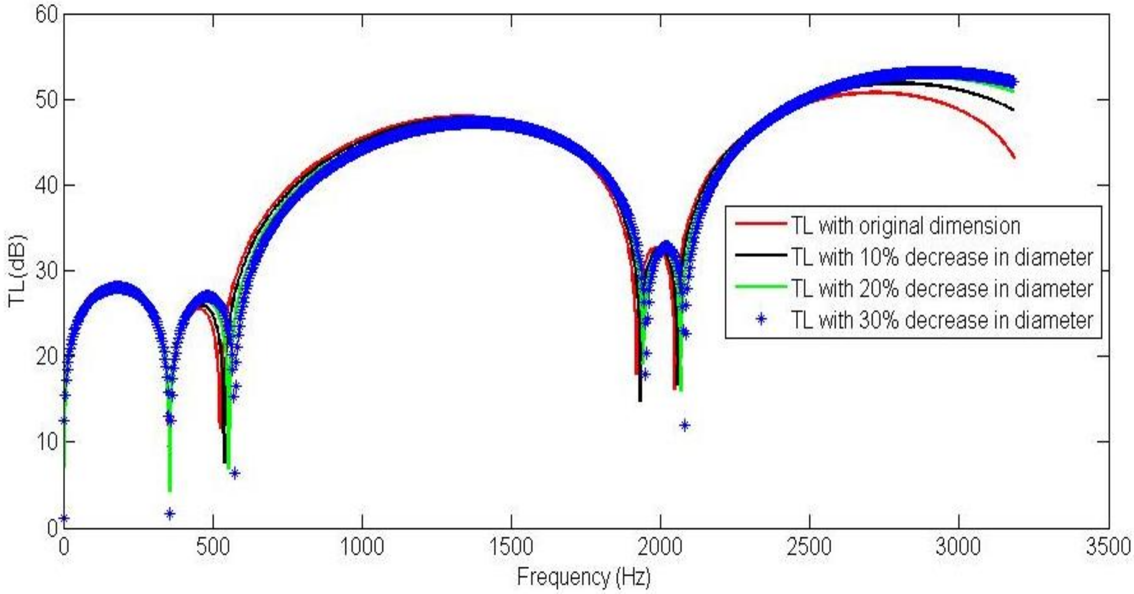


Figure 27. Noise transmission loss for decreasing silencer geometry

For the case 6, it is focused on the effects of outlet diameter:

Table 11. Effects of outlet diameter variations on the TL amounts

	L1 (inch)	L2 (inch)	L3 (inch)	d1 (inch)	d2 (inch)	d3 (inch)	TL (dB)	RMSTL (dB)
-30%	6	18	6	1	3.5	0.7	49.3319	40.2673
-20%	6	18	6	1	3.5	0.8	50.1318	41.0933
-10%	6	18	6	1	3.5	0.9	50.7449	41.7911
Original	6	18	6	1	3.5	1	51.1977	42.3747
+10%	6	18	6	1	3.5	1.5	51.5421	43.9275
+20%	6	18	6	1	3.5	2	52.3214	43.2078
+30%	6	18	6	1	3.5	2.5	53.0214	41.6634

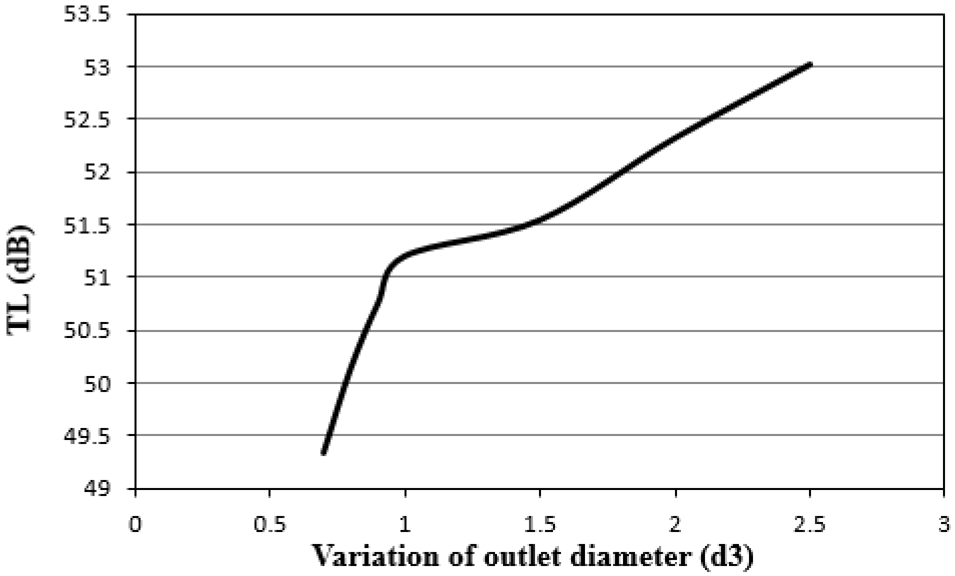


Figure 28. Noise transmission loss for decreasing outlet geometry

It is appeared from the table 11 and figure 28 that the behavior of outlet diameter is similar to the silencer length over the TL amounts. Figures 29 and 30 are presenting this factor as the safe element for maximization of TL over the wide frequency range. It means that the increasing the outlet diameter cause to enlarging the TL amounts.

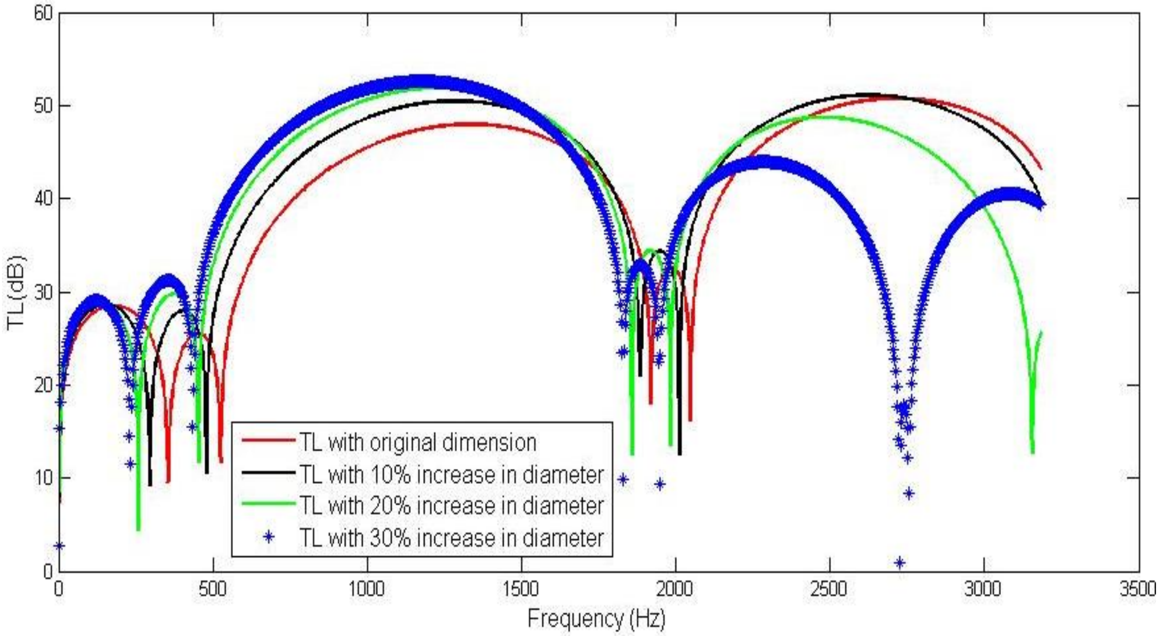


Figure 29. Noise transmission loss for increasing outlet geometry

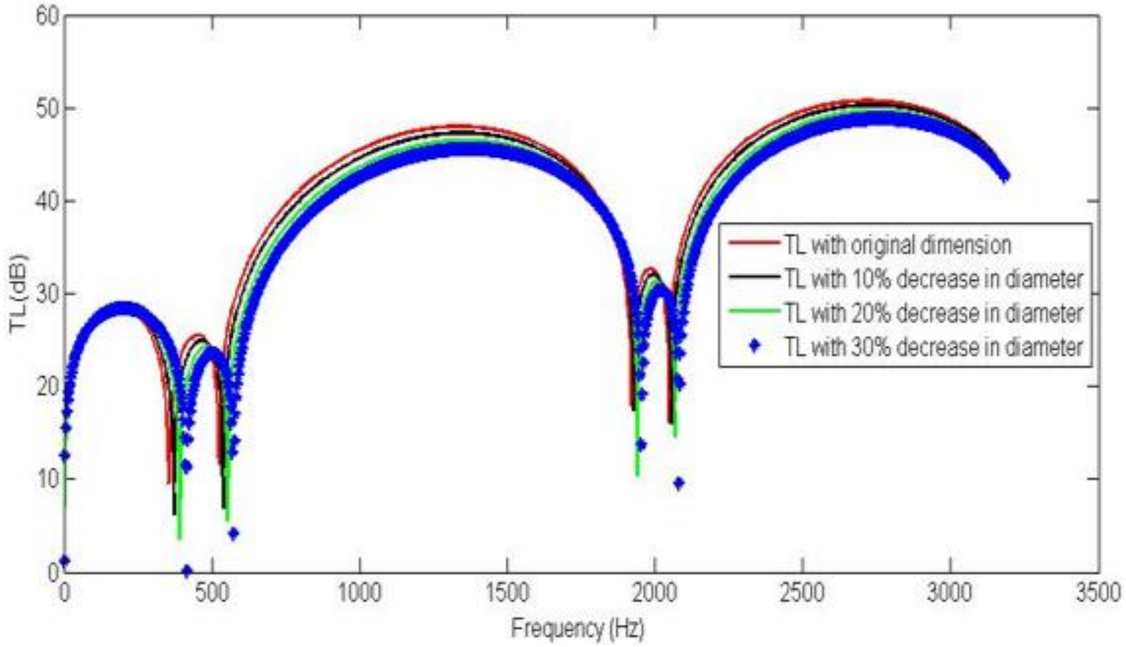


Figure 30. Noise transmission loss for reducing outlet geometry

As the cases showed us, length is a reliable factor for designing; however diameter is not trustworthy element. So, it is decided to apply genetic algorithm to find an optimum answer for the design of a muffler.

4.5 Results of Genetic Algorithm

This section will show the obtained optimum values of TL by using the GA algorithm for the Transfer-Matrix Method.

4.5.1 GA on the Transfer-Matrix Method

In this part, the function of GA code is shown by applying on Transfer Matrix Method without considering any intervals on the effective elements like length and diameters. The interval of frequency is 0 to 18000 Hz, the total number of generation 5, the number of population is 500, and the number of variables is 6 as it was mentioned before. Below figures show the related results:

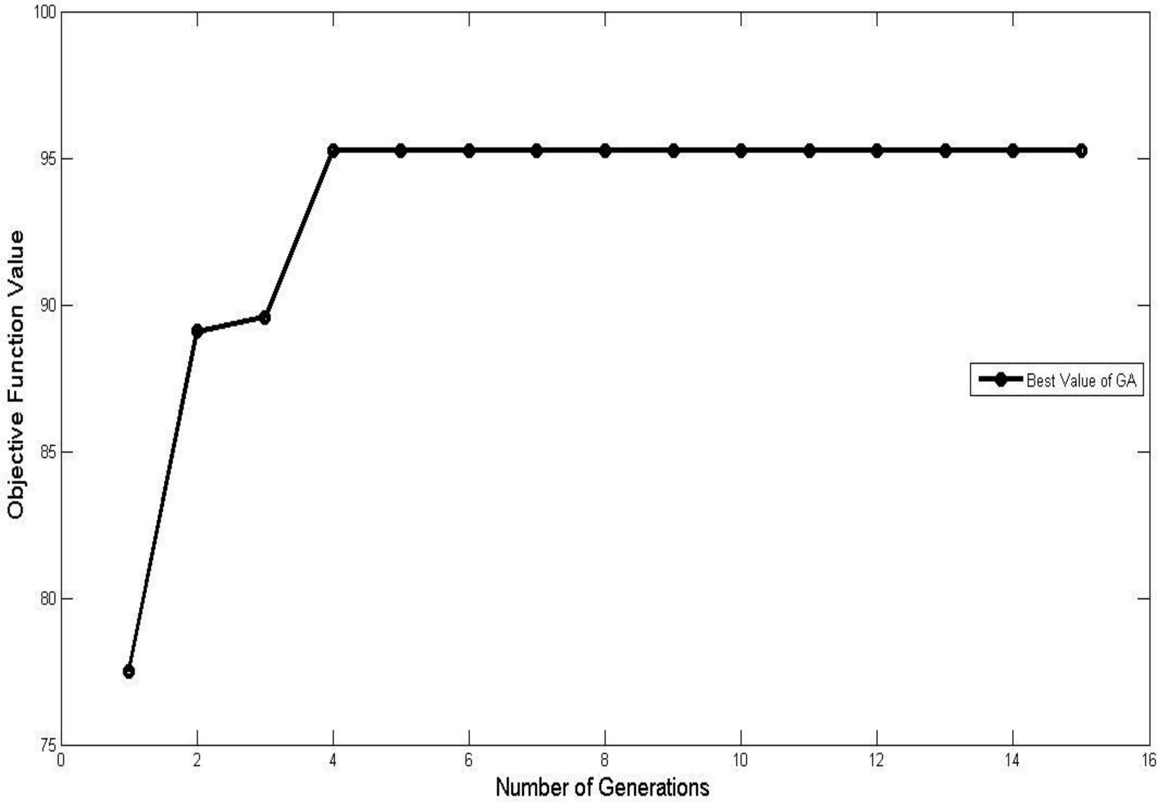


Figure 31. The performance of GA on the Transfer Matrix Method

The GA code is preparing the optimum value of length and diameter. Here, the fig. 31 is showing that the maximum value of GA is 95.24737 dB. The obtained amounts of length and diameter are applied in the developed code of TMM. Fig. 32 shows both amounts of TL whether obtained by TMM and GA for the comparison.

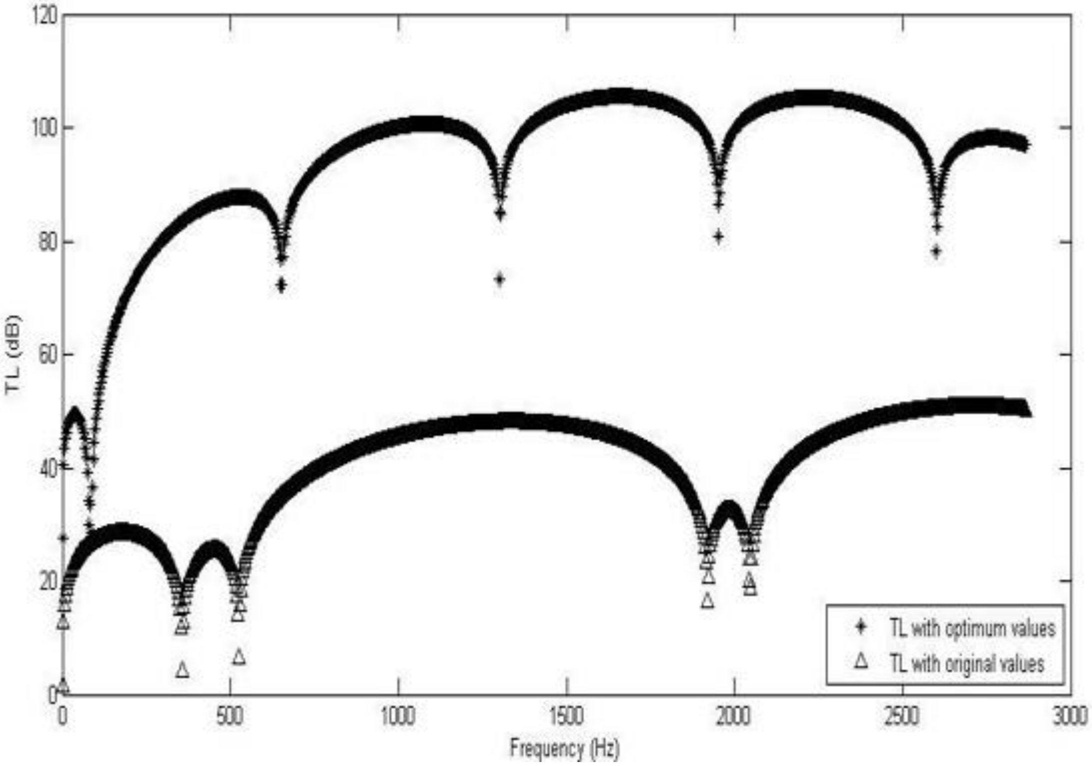


Figure 32. TL values by the optimum parameters of GA

These values are shown totally here to observe:

Table 12. TL values by the optimum parameters of GA in the TMM code

	Inlet Length (inches)	**Silencer Length (inches)**	**Outlet Length (inches)**	**Inlet Diameter (inches)**	**Silencer Diameter (inches)**	**Outlet Diameter (inches)**	**Max TL (dB)**	**RMSTL (dB)**
Optimum Values	0.3937	7.3889	0.3937	5.2336	2.1750	0.9817	105.75	51.20

As the fig. 19 shows us, three types of conclusion could be made which they are best value of Genetic Algorithm (GA), best value of RS of TL, and mean value of obtained of GA. The amount of best performance of GA is shown clearly in fig. 31 with 96 dB. In fig32, the upper curve is showing the mean amount of GA which is important for us to make decision. The point that has to be considered is that by increasing/decreasing the number of weather population or generation cannot guarantee the best value of the obtained GA because of the inherent of this method.

Since the considered design is taken from the existed dimension of a muffler in the MAP software, so these parameters were chosen arbitrary without considering any design model of a company or anywhere else. So, the aim of these results is showing the developed code is applicable for design and optimization. On the other hand, some new regulations are enacted by the EU which is called EU noise vehicle limits [39]. It is saying that the new standards should be applied to all new types of vehicles can be sold from 2019. The new limits would be 68 decibels for cars, 70 decibels for vans and 78 decibels for lorries. The regulation will also introduce a new noise test method for vehicles. The Directive 83/206/EEC is the END provides for the creation of noise maps and action plans in order to reduce environmental noise. [40]

Chapter 5

CONCLUSION AND FUTURE WORKS

The variation of noise transmission loss measurement in mufflers with respect to its dimensional parameters, i.e. in-, out-takes and silencer diameters and lengths, was studied and reported. At this regard, a self-written program was developed to calculate the value of TL for different shapes of mufflers.

In the first attempt, the three-point measurement of a TL was followed by computing the sound pressure level. By perusing among the results, it was specified that increasing of inlet diameter had the most significant influence on maximization of TL and it can be a spotlight for designing the shape of mufflers.

For practical applications, it was decided to modify the geometry of muffler over a narrow-band frequency, e.g., 200 Hz 1/3 octave band, while TL must be maximized. In fact, the maximization of TL over a wide frequency range is not useful for the real applications. The results of this study showed that the variation in the out-take area of muffler had no distinctive effect on maximization of TL. However, variation of the inlet tube was more effective on the Maximization of TL.

Later, Transfer Matrix Method was used to calculate the TL over a wide frequency range. The results presented that increment in the length of all in-, out-take and silencer plus increment of outtake diameter caused to increase the TL amount.

The genetic algorithm method is used to modify the geometry of a multi-chamber muffler and a sample result was presented. This optimization was done on the transfer matrix method because this method is more efficient in fast calculating the TL of a muffler and more feasible as well.

For the future work, it is suggested to do research on the shape modification of industrial mufflers to make them quieter. At this regard, usage of Helmholtz resonators which cancel the noise across the silencer duct will be necessary. Shape and location of resonators along with the shape and material of mufflers must be optimized at the same time via a multi-objective multi-variables optimization procedure.

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APPENDIX

Appendix: MATLAB code

```
function GA
% Genetic Algorithm(real coding)
% Goal: find maximum of function that introduced in fun00.m file in
current
% directory and can be plotted in plot00
% this file is also include the random serach for comparision
tic
clc
figure(1)
clf
clear all
format long

%------------------------        parameters        --------------------
----
% befor using this function you must specified your function in fun00.m
% file in current directory and then set the parameters
var=6;            % Number of variables (this item must be equal to the
                  %   number of variables that is used in the function
in
                  %   fun00.m file)
n=50;            % Number of population

m0=5;            % Number of generations that max value remains
constant
                  %   (use for termination criteria)
nmutationG=20;                  %number of mutation children(Gaussian)
nmutationR=20;                  %number of mutation children(random)
nelit=2;                        %number of elitism children
valuemin=ones(1,var)*0.01;     % min possible value of variables
valuemax=ones(1,var)*0.2;      % max possible value of variables

%----------------------------------------------------------------------
---
nmutation=nmutationG+nmutationR;
sigma=(valuemax-valuemin)/10;    %Parameter that related to Gaussian
                                 %   function and used in mutation step
max1=zeros(nelit,var);
parent=zeros(n,var);
cu=[valuemin(1) valuemax(1) valuemin(2) valuemax(2)];
for l=1:var
    p(:,l)=valuemin(l)+rand(n,1).*(valuemax(l)-valuemin(l));
end
initial=p;
m=m0;
maxvalue=ones(m,1)*-1e10;
maxvalue(m)=-1e5;
g=0;
meanvalue(m)=0;
%-------------   ****    termination criteria   ****-------------
while abs(maxvalue(m)-maxvalue(m-(m0-1)))>0.001*maxvalue(m) &...
        (abs(maxvalue(m))>1e-10 & abs(maxvalue(m-(m0-1)))>1e-10)...
```

```
        & m<10000 & abs(maxvalue(m)-meanvalue(m))>1e-5 | m<20
    sigma=sigma./(1.05);% reducing the sigma value
    %  ------  **** % reducing the number of mutation()random   **** --
--
    g=g+1;
    if g>10 & nmutationR>0
        g=0;
        nmutationR=nmutationR-1;
        nmutation=nmutationG+nmutationR;
    end

    %-------------   ****    function evaluation   ****-------------
    for i=1:n
        y(i)=fun00(p(i,:));
    end
    s=sort(y);
    maxvalue1(1:nelit)=s(n:-1:n-nelit+1);
    if nelit==0
        maxvalue1(1)=s(n);
        for i=1:n
            if y(i)==maxvalue1(1)
                max1(1,:)=p(i,:);
            end
        end
    end
    for k=1:nelit
        for i=1:n
            if y(i)==maxvalue1(k)
                max1(k,:)=p(i,:);
            end
        end
    end
    if var==2
        figure(1)
        subplot(2,2,1)
        hold off
        plot00(cu)
        hold on
        plot3(p(:,1),p(:,2),y,'ro')
        plot3(max1(1,1),max1(1,2),maxvalue1(1),'bh')
        title({' Genetic Algorithm '...
            ,'Performance of GA ( o : each individual)'},'color','b')

    end
    y=y-min(y)*1.02;
    sumd=y./sum(y);
    meanvalue=y./(sum(y)/n);


    %-------------   ****   Selection: Rolette wheel   ****------------
-
    for l=1:n
        sel=rand;
        sumds=0;
        j=1;
        while sumds<sel
```

```
            sumds=sumds+sumd(j);
            j=j+1;
        end
        parent(l,:)=p(j-1,:);
    end
    p=zeros(n,var);

    %-------------   ****    regeneration   ****-------------
    for l=1:var


        %-------------   ****    cross-over   ****-------------
        for j=1:ceil((n-nmutation-nelit)/2)
            t=rand*1.5-0.25;
            p(2*j-1,l)=t*parent(2*j-1,l)+(1-t)*parent(2*j,l);
            p(2*j,l)=t*parent(2*j,l)+(1-t)*parent(2*j-1,l);
        end


        %-------------   ****    elitism   ****-------------
        for k=1:nelit
            p((n-nmutation-k+1),l)=max1(k,l);
        end


        %-------------   ****    mutation   ****-------------
        for i=n-nmutation+1:n-nmutationR
            phi=1-2*rand;
            z=erfinv(phi)*(2^0.5);
            p(i,l)=z*sigma(l)+parent(i,l);

        end
        for i=n-nmutationR+1:n
            p(i,1:var)=valuemin(1:var)+rand(1,var).*(valuemax(1:var)-
...
                valuemin(1:var));
        end
        for i=1:n
            for l=1:var
                if p(i,l)<valuemin(l)
                    p(i,l)=valuemin(l);
                elseif p(i,l)>valuemax(l)
                    p(i,l)=valuemax(l);
                end
            end
        end
    end
    p;
    m=m+1;
    max1;
    maxvalue(m)=maxvalue1(1);
    maxvalue00(m-m0)=maxvalue1(1);
    mean00(m-m0)=sum(s)/n;
    meanvalue(m)=mean00(m-m0);
    figure(1)
```

```
    if var==2
        subplot(2,2,2)
    end
    hold off
    plot(maxvalue00,'b')
    hold on
    plot(mean00,'r')
    hold on
    title({'Performance of GA',...
        'best value GA:blue, best value RS:black, mean value 
GA:red',''}...
        ,'color','b')
    xlabel('number of generations')
    ylabel('value')



    %-------------   ****    Random search   ****-------------
    %-------------   ****   for comparision  ****-------------
    p00=zeros(n,var);
    for l=1:var
        p00(:,l)=valuemin(l)+rand(n,1).*(valuemax(l)-valuemin(l));
    end
    for i=1:n
        y(i)=fun00(p00(i,:));
    end
    s=sort(y);
    maxvalueRAND(m-m0)=s(n);
    if m>(m0+1)
        if maxvalueRAND(m-m0)<maxvalueRAND(m-(m0+1))
            maxvalueRAND(m-m0)=maxvalueRAND(m-(m0+1));
        else
            for i=1:n
                if y(i)==maxvalueRAND(m-m0)
                    maxRand=p00(i,:);
                end
            end
        end
    else
        for i=1:n
            if y(i)==maxvalueRAND(m-m0)
                maxRand=p00(i,:);
            end
        end
    end
    plot(maxvalueRAND,'k')
    if var==2
        figure(1)
        subplot(2,2,3)
        plot00(cu)
        hold on
        plot3(maxRand(1,1),maxRand(1,2),maxvalueRAND(m-m0),'k*')
        plot3(max1(1,1),max1(1,2),maxvalue00(m-m0),'bo')
        title({'Best solution found by GA(: o) & RS(:*)'...
            'in each generation ',''},'color','b')
    end
    pause(0.001)
end
```

```
clc
disp('     Genetic Algorithm(real coding)   ')
disp('          Good Bye          ')
disp('      Hello      ')
disp('**************************************')
num_of_fun_evaluation=n*m
max_point_GA=max1(1,:)
maxvalue_GA=maxvalue00(m-m0)
max_point_RS=maxRand
maxvalue_RS=maxvalueRAND(m-m0)
if var==2
    figure(1)
    subplot(2,2,4)
    hold off
    plot3(max1(1,1),max1(1,2),maxvalue1,'o')
    hold on
    plot00(cu)
    hold on
    plot3(maxRand(1,1),maxRand(1,2),maxvalueRAND(m-m0),'*')
    title({'Best solution ';'GA: o & RS: *'},'color','b')
end
figure(2)
title('Performance of GA(best value)','color','b')
xlabel('number of generations')
ylabel('max value of best solution')
hold on
plot(maxvalue00)
disp(max1)
hold on
toc
```