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Design optimization of double-chamber mufflers on constrained venting system by GA method

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Whilst the space volume of mufflers in a noise control system is often constrained for maintenance in practical engineering work, the maximization on muffler's performance becomes important and essential. To efficiently depress the venting noise, a high performance of double-chamber muffler is then proposed and investigated in this paper. To assess the optimal solution in the muffler design, the genetic algorithm (*GA*), a stochastic algorithm, is also applied, accordingly.

This paper presents the *GA* application for the size optimal design of double-chamber muffler under space constraints and dealing with broadband noise. Using technique of four-pole matrix for sound transmission loss (*STL*) calculation in conjunction with the GA technique, the optimisation was carried out.

Before *GA* operation, a single-chamber muffler is simulated and compared with the experimental data for accuracy check of mathematical model. Thereafter, a simple program of noise control at the pure tone of 500 Hz has been pre-run to verify the correctness of genetic algorithm before the optimal design of broadband noise was performed. Results show that both the accuracy of mathematical model and the correctness of *GA* method are acceptable. Consequently, the *GA* optimization on double-chamber muffler proposed in this study may provide a quick and correct approach.

Keywords: double-chamber muffler; four-pole matrix method; sound transmission loss; space constraints; GA optimization

INTRODUCTION

As high noise levels can be harmful to workers and can lead not only to psychological but also physiological ailment, the attention of noise control on equipment is then focused gradually. To eliminate the noise value of venting system, muffler is habitually in use [1]. However, the space of muffler is often limited as required by operation and maintenance. And even if many researches of muffler designs have been well addressed, the discussion of optimal design under space constraints is rarely emphasized. In the previous work by Yeh et al. [2], the graphical analysis of optimal shape design to improve the performance of sound transmission loss (*STL*) on a constrained single expansion muffler was discussed.

To efficiently depress the noise emitted from venting system, the sizing optimization of constrained double-chamber muffler with extended tubes by mathematical gradient methods

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was explored and discussed by Yeh et al. [3]. However it is troublesome to seek for a good starting point during the different gradient-based optimal processes even in the exterior penalty function method or the interior penalty function method. Therefore, the new optimizer of genetic algorithm is thus introduced.

GA optimizers are robust, stochastic search methods modeled on the concepts of natural selection and evolution [4]. Unlike the traditional gradient-based method, which needs the derivatives and the good starting point in the objective function, *GA* optimizers are able to locate easily the global optimum in a near optimal manner. In this paper, *GA* is coupled with the transfer matrix method, based on the plane wave theory, to optimize the performance of muffler on constrained venting system.

1. THEORETICAL BACKGROUND

The whole inside flow condition of the double-chamber muffler represented by ten chosen nodes (pt1~pt10) is shown in Figure 1. As deduced by Prasad, Crocker and Munjal [5, 6, 7], the individual transfer matrix in each element is simply expressed as (designations are in nomenclature section)

$$\begin{pmatrix} p_1 \\ \rho_o c_o u_1 \end{pmatrix} = e^{-jM_1 kL_1/(1-M_1^2)} \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{pmatrix} p_2 \\ \rho_o c_o u_2 \end{pmatrix}, \tag{1a}$$

where

$$b_{11} = \cos\left(\frac{kL_1}{1-M_1^2}\right); b_{12} = j\sin\left(\frac{kL_1}{1-M_1^2}\right); b_{21} = j\sin\left(\frac{kL_1}{1-M_1^2}\right); b_{22} = \cos\left(\frac{kL_1}{1-M_1^2}\right); \tag{1b}$$

$$\begin{pmatrix} p_2 \\ \rho_o c_o u_2 \end{pmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & S_2/S_1 \end{bmatrix} \begin{pmatrix} p_3 \\ \rho_o c_o u_3 \end{pmatrix}; \tag{2}$$

$$\begin{pmatrix} p_3 \\ \rho_o c_o u_3 \end{pmatrix} = e^{-jM_2 kL_2/(1-M_2^2)} \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{pmatrix} p_4 \\ \rho_o c_o u_4 \end{pmatrix}, \tag{3a}$$

where

$$c_{11} = \cos\left(\frac{kL_2}{1-M_2^2}\right); c_{12} = j\sin\left(\frac{kL_2}{1-M_2^2}\right); c_{21} = j\sin\left(\frac{kL_2}{1-M_2^2}\right); c_{22} = \cos\left(\frac{kL_2}{1-M_2^2}\right); \tag{3b}$$

$$\begin{pmatrix} p_4 \\ \rho_o c_o u_4 \end{pmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & S_3/S_2 \end{bmatrix} \begin{pmatrix} p_5 \\ \rho_o c_o u_5 \end{pmatrix}; \tag{4}$$

$$\begin{pmatrix} p_5 \\ \rho_o c_o u_5 \end{pmatrix} = e^{-jM_3 kL_3/(1-M_3^2)} \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} \begin{pmatrix} p_6 \\ \rho_o c_o u_6 \end{pmatrix}, \tag{5a}$$

where

$$d_{11} = \cos\left(\frac{kL_3}{1-M_3^2}\right); d_{12} = j\sin\left(\frac{kL_3}{1-M_3^2}\right); d_{21} = j\sin\left(\frac{kL_3}{1-M_3^2}\right); d_{22} = \cos\left(\frac{kL_3}{1-M_3^2}\right); \tag{5b}$$

$$\begin{pmatrix} p_6 \\ \rho_o c_o u_6 \end{pmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & S_4/S_3 \end{bmatrix} \begin{pmatrix} p_7 \\ \rho_o c_o u_7 \end{pmatrix}; \tag{6}$$

$$\begin{pmatrix} p_7 \\ \rho_o c_o u_7 \end{pmatrix} = e^{-jM_4 kL_4/(1-M_4^2)} \begin{bmatrix} e_{11} & e_{12} \\ e_{21} & e_{22} \end{bmatrix} \begin{pmatrix} p_8 \\ \rho_o c_o u_8 \end{pmatrix}, \tag{7a}$$

where

$$e_{11} = \cos\left(\frac{kL_4}{1-M_4^2}\right); e_{12} = j\sin\left(\frac{kL_4}{1-M_4^2}\right); e_{21} = j\sin\left(\frac{kL_4}{1-M_4^2}\right); e_{22} = \cos\left(\frac{kL_4}{1-M_4^2}\right); \tag{7b}$$

$$\begin{pmatrix} p_8 \\ \rho_o c_o u_8 \end{pmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & S_5/S_4 \end{bmatrix} \begin{pmatrix} p_9 \\ \rho_o c_o u_9 \end{pmatrix}; \tag{8}$$

$$\begin{pmatrix} p_9 \\ \rho_o c_o u_9 \end{pmatrix} = e^{-jM_5 kL_5/(1-M_5^2)} \begin{bmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{bmatrix} \begin{pmatrix} p_{10} \\ \rho_o c_o u_{10} \end{pmatrix}, \tag{9a}$$

where

$$f_{11} = \cos\left(\frac{kL_5}{1-M_5^2}\right); f_{12} = j\sin\left(\frac{kL_5}{1-M_5^2}\right); f_{21} = j\sin\left(\frac{kL_5}{1-M_5^2}\right); f_{22} = \cos\left(\frac{kL_5}{1-M_5^2}\right); \tag{9b}$$

By using the matrix substitution on equations (1)–(9), the complete system matrix is

$$\begin{pmatrix} p_1 \\ \rho_o c_o u_1 \end{pmatrix} = e^{-jk\left(\frac{M_1L_1}{1-M_1^2}+\frac{M_2L_2}{1-M_2^2}+\frac{M_3L_3}{1-M_3^2}+\frac{M_4L_4}{1-M_4^2}+\frac{M_5L_5}{1-M_5^2}\right)} \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \frac{S_2}{S_1} \end{bmatrix} \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \frac{S_3}{S_2} \end{bmatrix}$$
$$\begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \frac{S_4}{S_3} \end{bmatrix} \begin{bmatrix} e_{11} & e_{12} \\ e_{21} & e_{22} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \frac{S_5}{S_4} \end{bmatrix} \begin{bmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{bmatrix} \begin{pmatrix} p_{10} \\ \rho_o c_o u_{10} \end{pmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{pmatrix} p_{10} \\ \rho_o c_o u_{10} \end{pmatrix}. \tag{10}$$

Consequently, the *STL* of a muffler is [7]

$$STL(f, Q, L_1, L_2, L_3, L_4, L_5, D_o, D_1, D_3, D_5) = 20\log\left(\frac{|T_{11}+T_{12}+T_{21}+T_{22}|}{2}\right) + 10\log\left(\frac{S_1}{S_{10}}\right). \tag{11}$$

To reduce the parameters in *STL* function, not only the constraint condition but also the new parameter rt_1 are introduced as

$$rt_1 = \frac{L_4}{L_2};\ L_2 = L_o - L_1 - L_3 - L_4 - L_5;\ D_o = constant;\ L_o = constant. \tag{12}$$

An alternative form of Eq. (11) is expressed as

$$STL(f, Q, L_1, L_3, L_5, rt_1, D_1, D_3, D_5) = 20\log\left(\frac{|T_{11}+T_{12}+T_{21}+T_{22}|}{2}\right) + 10\log\left(\frac{S_1}{S_{10}}\right). \tag{13}$$

The sound pressure level (SPL_i) at muffler outlet with respect to the octave frequency *i*, yields

$$SPL_i = SPL_{oi} - STL_i, \tag{14}$$

where SPL_{oi} is the *SPL* at the muffler inlet (or pipe outlet) without reflection effect, and STL_i is the muffler's *STL* with respect to the relative octave band frequency *i*.

Finally, the overall sound pressure level, SPL_T , at muffler outlet without reflection is expressed as:

$$SPL_T(Q, L_1, L_3, L_5, rt_1, D_1, D_3, D_5) = 10\log\left(\sum_{i=1}^{8} 10^{SPL_i/10}\right). \quad (15)$$

By using the formula of Eq. (13), the objective function used in *GA* optimization with respect to muffler is

$$OBJ = SPL_T(Q, L_1, L_3, L_5, rt_1, D_1, D_3, D_5)\,. \quad (16)$$

2. MODEL CHECKS

Before performing the *GA* optimal simulation on mufflers, the accuracy check of mathematical model on the fundamental element of a single-chamber muffler is performed by experimental data [8]. As depicted in Figure 2, the accuracy comparison between the theoretical and experimental data for the models is in good agreement. Therefore, the proposed fundamental mathematical model is acceptable. Consequently, the model linked with numerical method is applied for the sizing optimization in the following section.

3. GENETIC ALGORITHM

The concept of Genetic Algorithms, first formalized by Holland [9] and extended to functional optimization by Jong [10] later, involves the use of optimization search strategies patterned after Darwinian notion of natural selection and evolution. During a *GA* optimization, a set of trial solutions is chosen and "evolves" toward an optimal solution. In the following, we give a short description of the genetic algorithm, which is applied as the optimizer in the sizing optimization of double-chamber muffler.

A. Populations and Chromosomes

The initial population is built up by randomization. The parameter set is encoded to form a string, which represents the chromosome. As the bit length of the chromosome, was chosen as *bit_n*, the interval of the kth design parameter with $[Lb,Ub]_k$ was thereafter mapped to the band of binary value. The mapping system between the variable interval of $[Lb,Ub]_k$ and the kth binary chromosome of $[000...000 - 111...111]_k$ was then built.

By evaluation of the objective function (*OBJ*), each chromosome is assigned with the fitness.

B. Parents

By using the probabilistic computation weighted by the relative fitness, pairs of chromosome are selected as the candidate parents. The weighted roulette wheel selection is then applied. Each individual in the population is assigned space on the roulette wheel, which is proportional to the individual relative fitness. For *n* set of candidate parent, the weighted roulette wheel for the kk^{th} individual was represented as $\left(fitness_{kk} \Big/ \sum_{i=1}^{n} fitness_i\right)\cdot 100\%$. Individuals with the largest portion on the wheel have the greatest probability to be selected as parent generation for the next generation.

C. Offspring

One pair of offspring is generated from the selected parent (mating pool) by crossover. Crossover occurs with a probability of *pc*. Both the random selection of a crossover and combination of the two parent's genetic data are then proceeded. The scheme of single-point crossover is chosen in *GA*'s optimization.

Recombination and parent selection is the principle method for the evolution in *GA*.

D. Mutation

Genetically, mutation occurs with a probability of *pm* of which the new and unexpected point will be brought into the *GA* optimizer's search domain. It's an essential operation to keep the diversity of *GA* population and then improve the accuracy of *GA*'s optimization.

E. Elitism

To keep the best gene and improve the accuracy of optimization during reproduction, the elitism scheme in the parent generations is thus presented and developed.

F. New Generation

Reproduction includes selection, crossover, mutation and elitism. The reduplication continues until a new generation is constructed and the original generation is substituted. Highly fit characteristics produce more copies of themselves in subsequent generation resulting in a movement of the population towards an optimal direction. The process can be terminated when a number of generations exceed a pre-selected value of *gen_no*.

The operation in *GA* method is pictured as Figure 3. In addition, the *GA* optimizer developed for *SPL* minimization at exit of muffler is depicted in Figure 4.

4. *GA* OPTIMIZATION

4.1. Case Study

A noise control of diesel engine noise at the exhausted outlet shown in Figure 5 is introduced as the numerical case. The overall sound pressure level (*SPL*) inside the diesel engine's outlet pipe is 105.6 dB. In addition, the sound pressure spectrum in octave band is shown as below:

f, Hz	31.5	63	125	250	500	1k	2k	4k	8k
SPL, dB	86	90	94	93	104	95	91	88	64

The available space for muffler is 0.3 meter in width, 0.3 meter in height and 1.0 meter in length. By equation (16), seven design parameters are chosen in *GA* optimization. To avoid the larger pressure drop and the flow-generated noise to occur in muffler [11], the minimal diameters (venting device) at D_1, D_3 and D_5 are specified to no less than 0.0762 (m). In addition, for the ease of manufacture in mufflers, each segment of muffler is limited to not less than 0.1 (m).

A series of assumptions of the constrained condition in design are illustrated as $0.0762\ (\mathrm{m}) \le D_1 \le 0.3\ (\mathrm{m})$; $0.0762\ (\mathrm{m}) \le D_3 \le 0.3\ (\mathrm{m})$; $0.0762\ (\mathrm{m}) \le D_5 \le 0.3\ (\mathrm{m})$; $0.1\ (\mathrm{m}) \le L_1 \le 0.2\ (\mathrm{m})$; $0.1\ (\mathrm{m}) \le L_3 \le 0.2\ (\mathrm{m})$; $0.1\ (\mathrm{m}) \le L_5 \le 0.2\ (\mathrm{m})$; $0.5 \le rt_1 \le 2$; $D_2 = D_4 = D_o = 0.3\ (\mathrm{m})$.

The design volume flow rate (Q) is confined to 0.8 (m^3/s).

4.2. Correctness on GA

Before the minimization of *SPL* in full band noise reduction is performed, a simple optimal program in maximizing the *STL* at the desired pure tone of 500 Hz has been pre-run. To obtain the accurate design by *GA* optimization, the larger number of population (*popuSize*), generation (*gen_no*) and bit length (*bit_n*) are set to 60, 500 and 40 respectively. Both the typical ratio crossover (*pc*) and mutation ratio (*pm*) used in following *GA* optimization are chosen as 0.8 and 0.05 independently [12].

The optimal results are listed and plotted in Table 1 and Figure 6 respectively. As the result indicated in Figure 6, the optimal *STL* of double-chamber mufflers is tuned and maximized at the desired frequency of 500 Hz by the *GA* optimization. Consequently, the correctness by using *GA* optimization technique is acceptable.

5. RESULTS AND DISCUSSION

5.1. Results

5.1.1. Effect on GA operators

As described in Section 4.2, the larger number of population (*popuSize*), generation (*gen_no*) and bit length (*bit_n*) are also set to 60, 500 and 40 individually. To identify the effects among *GA* operators, four trial cases with different values of control parameters (*pc*, *pm* and *elt_no*) are thus varied and discussed. Four cases chosen are described as follows:

A. Case 1: pc=0.8, pm=0.05, elt_no=1

By using the crossover of 0.8 and mutation of 0.05, the *GA* optimization is proceeded and accompanied with an elitism of 1. The result shows that the best generation occurred at generation #463. The best values of design parameters – D_1, D_3, D_5, L_1, L_3, L_5, rt_1 – are found to be 0.0762 (m), 0.2998 (m), 0.0762 (m), 0.1001 (m), 0.1717 (m), 0.1000 (m) and 1.2283 individually. The optimal value of *SPL* on muffler is 93.6 dB(A) with respect to these design parameters. In addition, the computation time of optimization process in personal computer is 3.30 minutes. *GA* optimization response with respect to generations is shown in Figure 7. As indicated in Figure 7, it reveals that the optimal process is obviously stable and more aggressive.

B. Case 2: pc=0.8, pm=0.05, elt_no=0

By using the crossover of 0.8 and mutation of 0.05, the *GA* optimization is proceeded and accompanied with an elitism of 0. The result shows that the best generation occurred at generation #463. The best values of design parameters – D_1, D_3, D_5, L_1, L_3, L_5, rt_1 – are found to be 0.0792 (m), 0.2811 (m), 0.0771 (m), 0.1011 (m), 0.1349 (m), 0.1315 (m) and 0.7588 individually. The optimal value of *SPL* on muffler is 95.0 dB(A) with respect to corresponding design parameters. In addition, the computation time of optimization process in personal computer is 3.41 minutes. *GA* optimization response with respect to generations is shown in Figure 8. As the result of Figure 8, the fluctuation of best solution is found to be violent. By no means, the *GA* optimal process becomes unstable with the lack of elitism scheme.

C. Case 3: pc=0.8, pm=0, elt_no=1

By using the crossover of 0.8 and mutation of 0.0, the *GA* optimization is proceeded and accompanied with an elitism of 1. The result shows that the best generation occurred at generation #108. The best values of design parameters – D_1, D_3, D_5, L_1, L_3, L_5, rt_1 – are found to be 0.0762 (m), 0.2930 (m), 0.0763 (m), 0.1467 (m), 0.1269 (m), 0.1019 (m) and 0.7832 individually. The optimal value of *SPL* on muffler is 94.5 dB(A) with respect to these design parameters. In addition, the computation time of optimization process in personal computer is 3.40 minutes. *GA* optimization response with respect to generations is shown in Figure 9. It is obvious that the diversity of population is insufficient after a long term of generation. Therefore, a worse solution will be obtained due to the lack of mutation scheme.

D. Case 4: pc=0, pm=0.05, elt_no=1

By using the crossover of 0.0 and mutation of 0.05, the *GA* optimization is proceeded and accompanied with an elitism of 1. The result shows that the best generation occurred at generation #365. The best values of design parameters – D_1, D_3, D_5, L_1, L_3, L_5, rt_1 – are found to be 0.0836 (m), 0.2597 (m), 0.0767 (m), 0.1540 (m), 0.1848 (m), 0.1006 (m) and 1.5509 individually. The optimal value of *SPL* on muffler is 95.5 dB(A) with respect to corresponding design parameters. In addition, the computation time of optimization process in personal computer is 3.25 minutes. *GA* optimization response with respect to generations is shown in Figure 10. It is found that the optimization is inert with the lack of crossover scheme.

The comparison of optimization for four cases is illustrated in Table 2. As indicated in Table 2, the first case in which crossover and mutation/elitism were applied has the minimal value of *SPL* compared with other cases.

5.1.2. Simulations

As discussed in Section 5.1.1, the *GA* parameters of crossover mutation and elitism with respect to 0.8, 0.05 and 1 are applied in the following optimization.

Because of the randomization of initial populations in *GA* optimization, ten times of simulation are carried out for the more accuracy purpose. The optimal *SPL* with respect to different random initial populations are depicted in Table 3.

5.2. Discussion

As indicated in Table 3, even though the initial populations are different, the deviations of the resultant *SPL* are trivial. Besides, it is found in each simulation that the design parameters of D_1, D_3 and D_5 are almost to be consistent with the values of 0.0762, 0.2996 and 0.0762 respectively in each simulation. It implied that they are the primary design parameters and was converged in the muffler optimization. Among them, the third set with resultant *SPL* of 93.60 dB(A) is identified as the best simulation. The related optimal *STL* with respect to spectrum is plotted and shown in Figure 11. In addition, a performance curve of muffler at the muffler's pipe outlet is shown in Figure 12. As indicated in Figure 12, the noise reduction of muffler with respect to spectrum is obvious. Consequently, the optimal shape of muffler with respect to the best design set is shown in Figure 13.

In addition, an average of the ten sets of design data were made and shown in Table 3. By taking the averaged design data into calculation, the corresponding *SPL* of 93.61 dB was then obtained. Obviously, it is still within the region of the tenth simulated results.

6. CONCLUSION

It has been shown that *GA* can be used in the optimization of noise control on venting system by adjusting the size of muffler under the space constraints. As indicated in Table 3, the difference of resultant *SPL* with respect to different random initial population is trivial. Therefore, *GA* becomes easier to use. The case study reveals that each of crossover, mutation and elitism plays an essential role in *GA* optimization.

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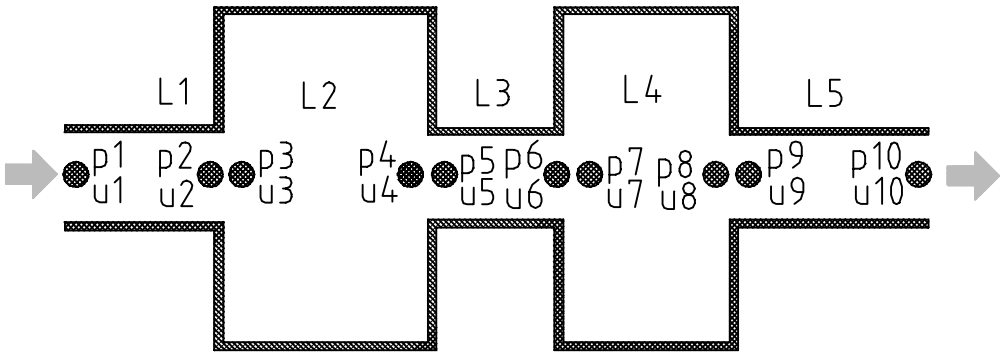

Figure 1. Flow condition for a double-chamber muffler

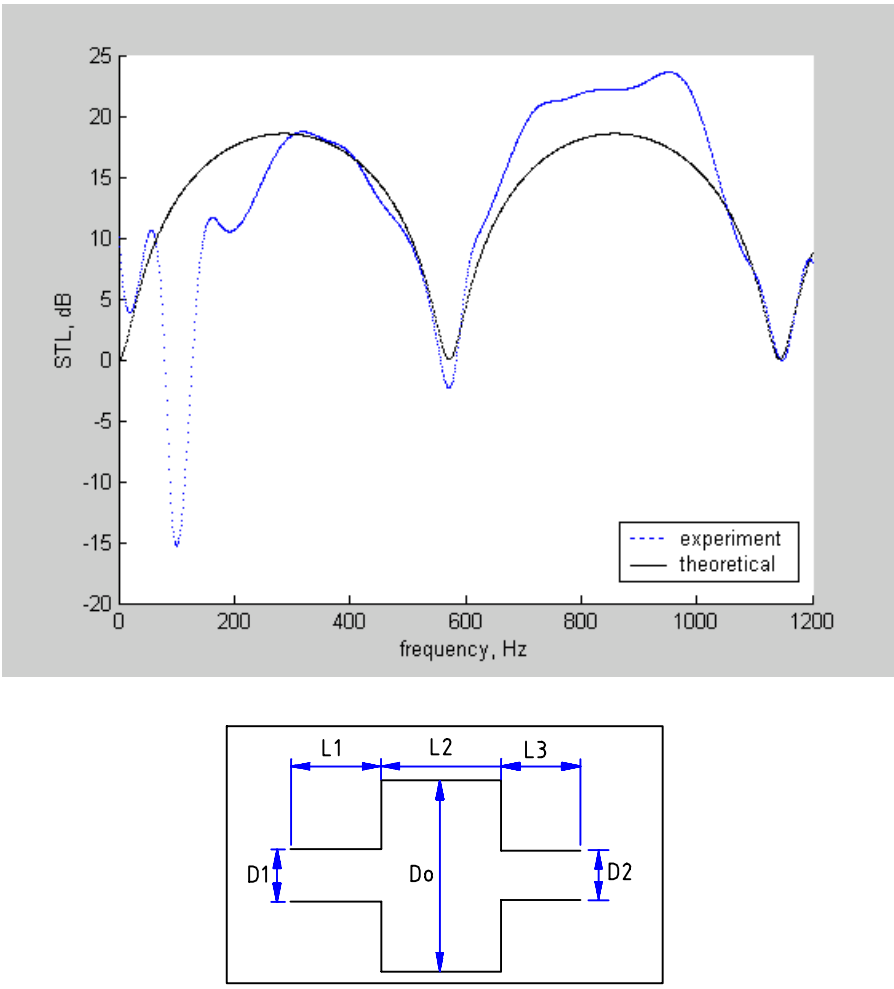

Figure 2. Performance of a single-chamber muffler without the mean flow
D_1=D_2=0.0365 (m), D_o=0.15 (m), L_1=L_3=0.1 (m), L_2=0.3 (m)

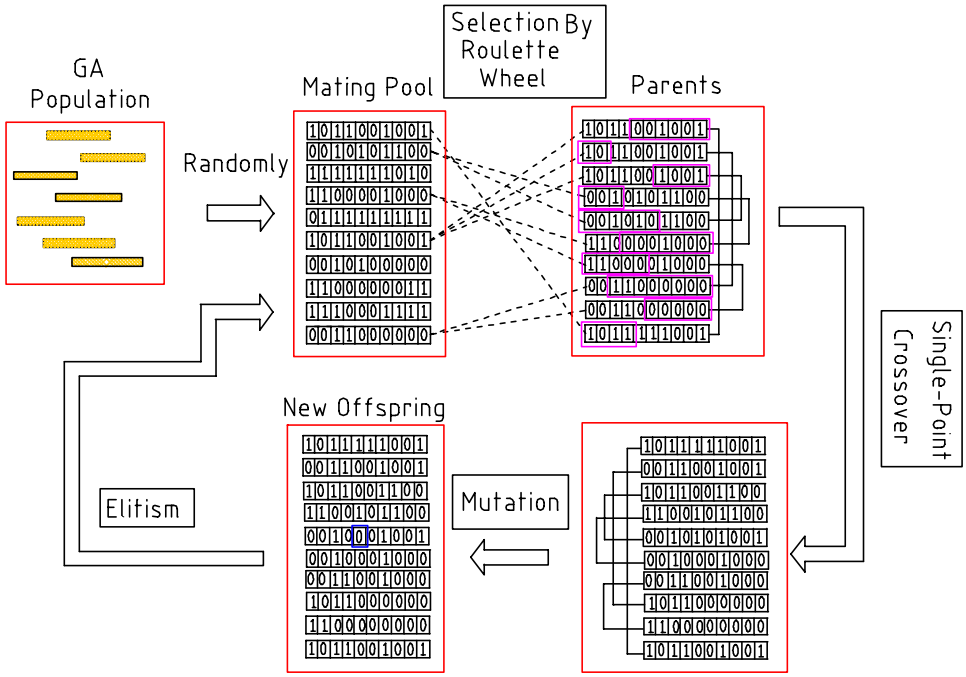

Figure 3. Operations in *GA* method

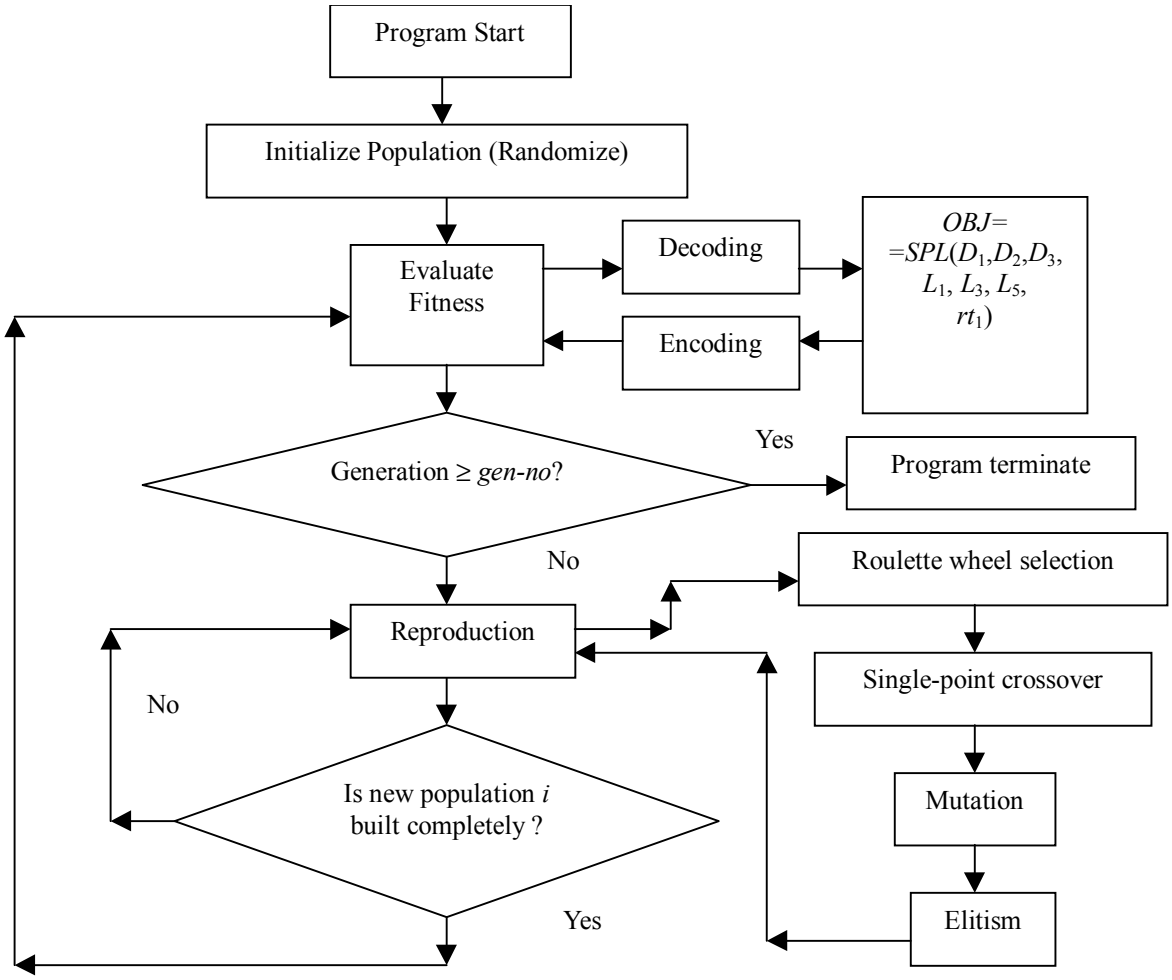

Figure 4. Block diagram of the *GA* optimization on muffler

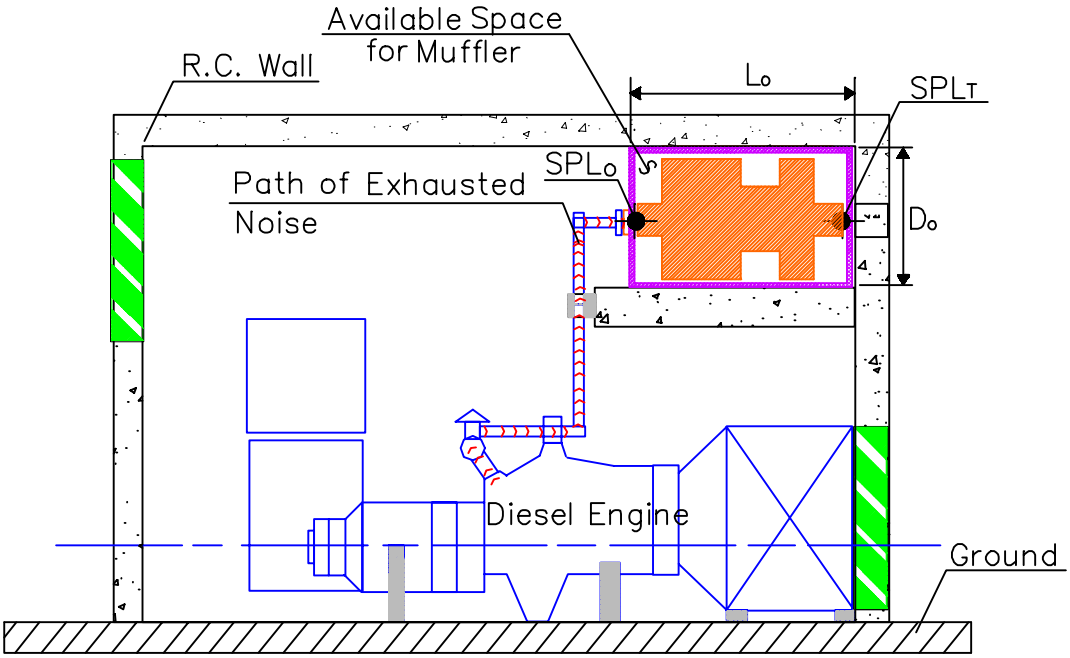

Figure 5. Elevation plan of noise control system in diesel engine room

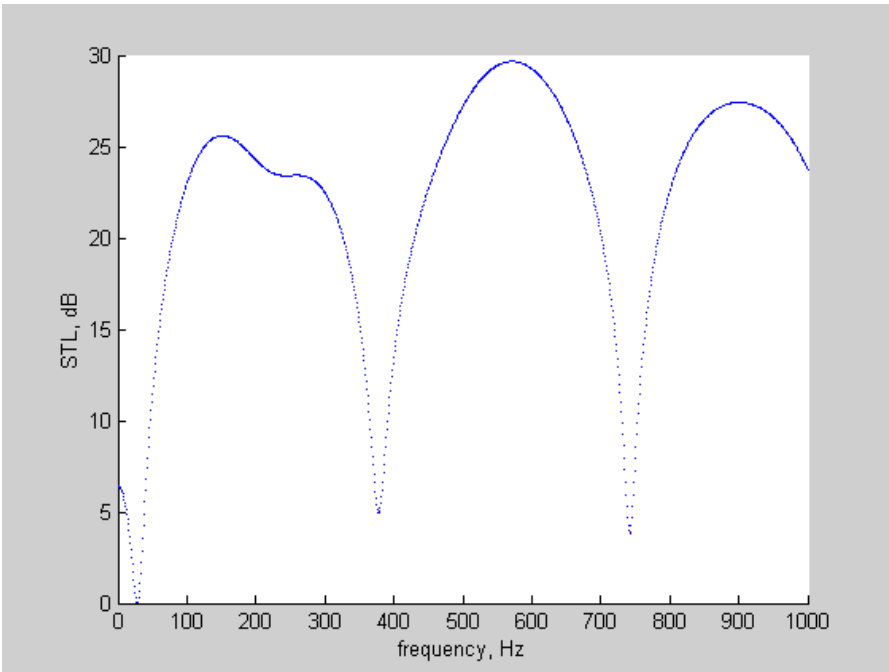

Figure 6. *STL* of muffler with respect to frequency domain
(*GA* Optimization at 500 Hz)

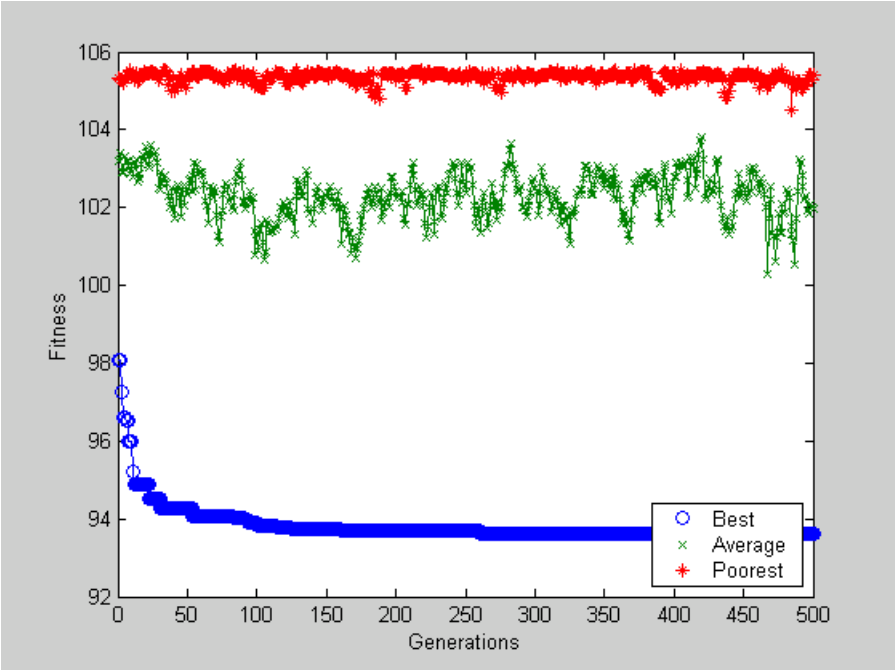

Figure 7. Response of *GA* optimization with respect to generations at case 1

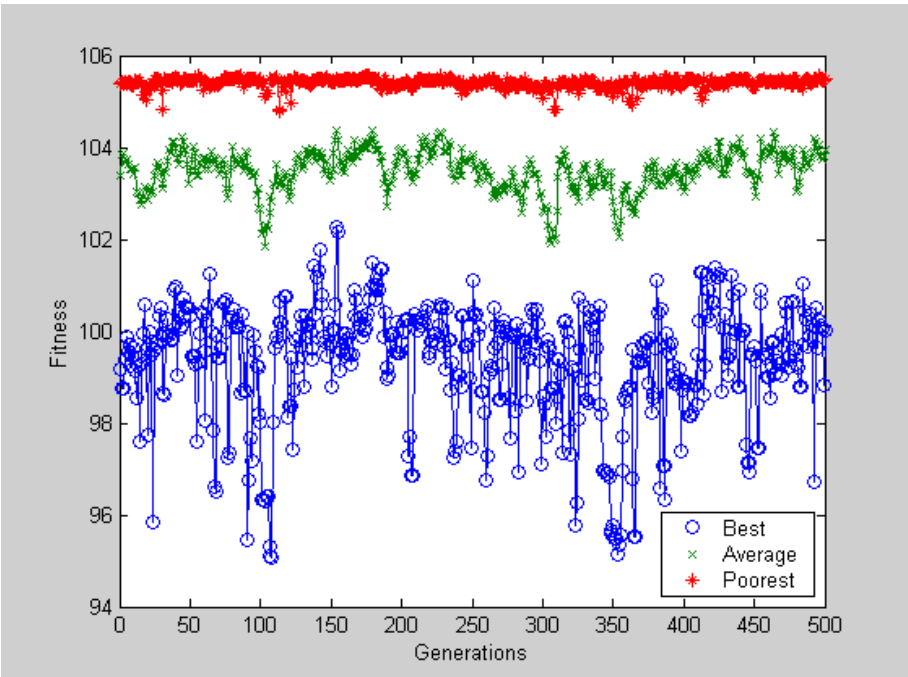

Figure 8. Response of *GA* optimization with respect to generations at case 2

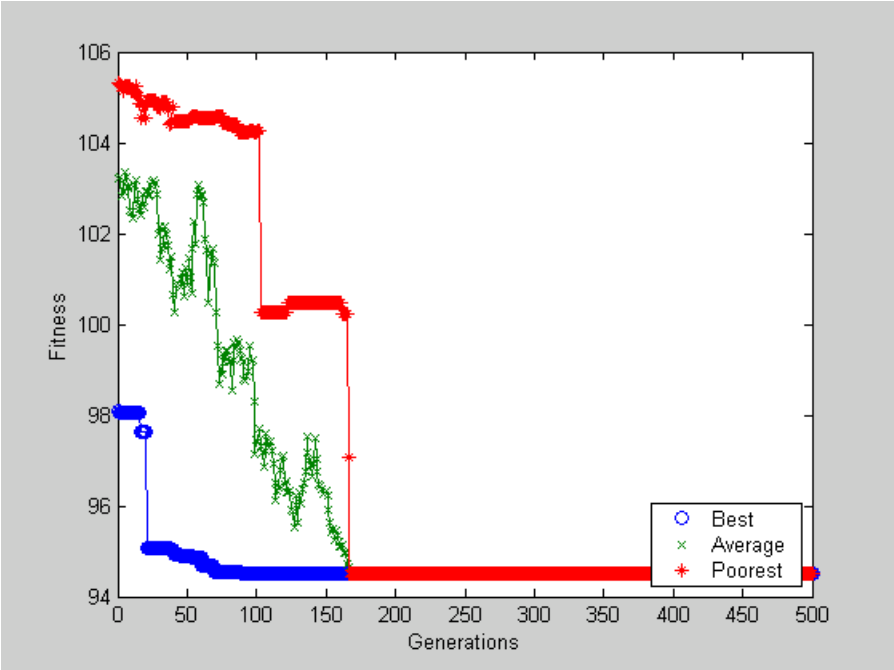

Figure 9. Response of *GA* optimization with respect to generations at case 3

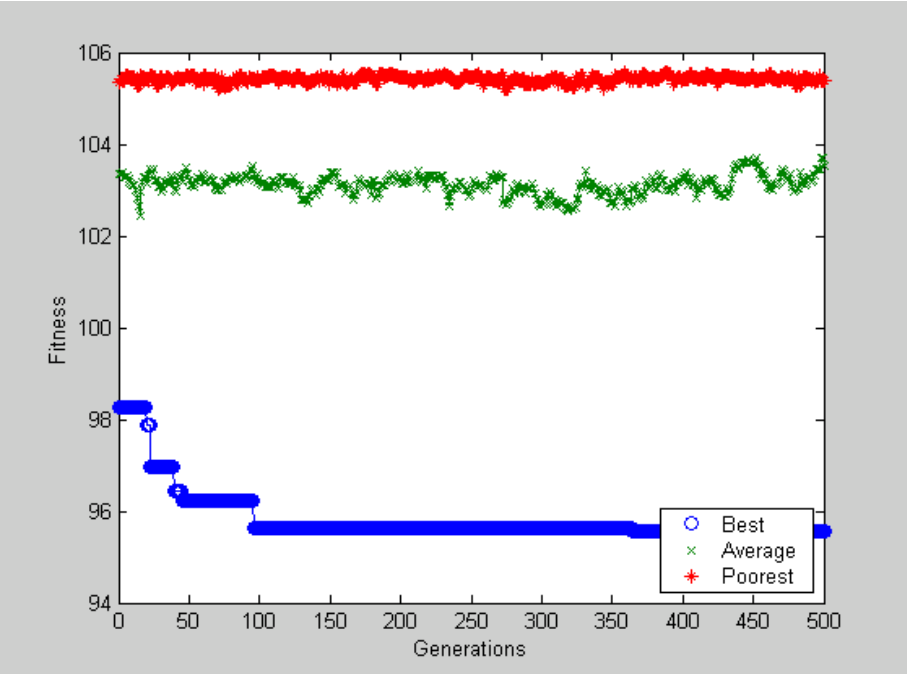

Figure 10. Response of *GA* optimization with respect to generations at case 4

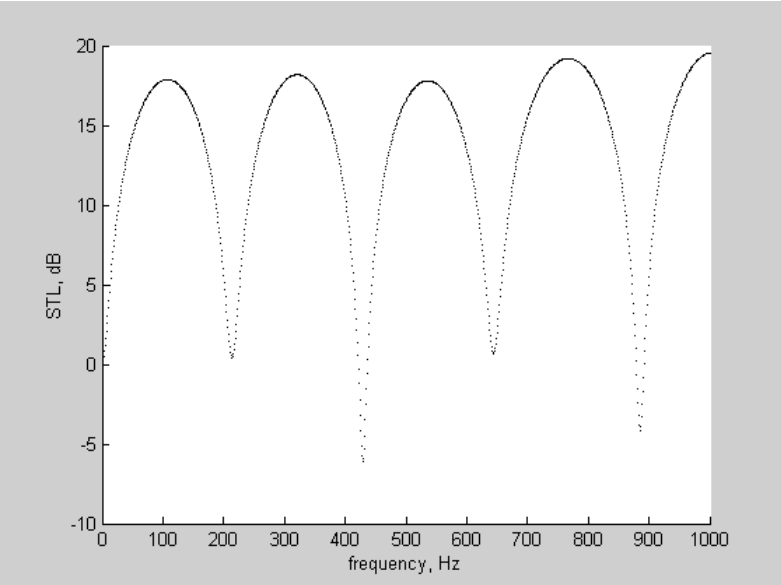

Figure 11. Optimal *STL* with respect to spectrum (case 1)

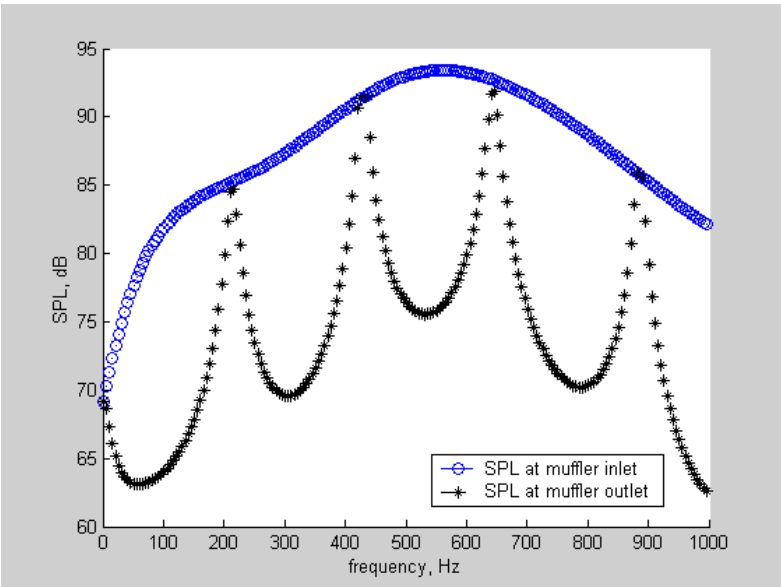

Figure 12. A comparison of *SPL* between muffler's inlet and outlet (case 1)

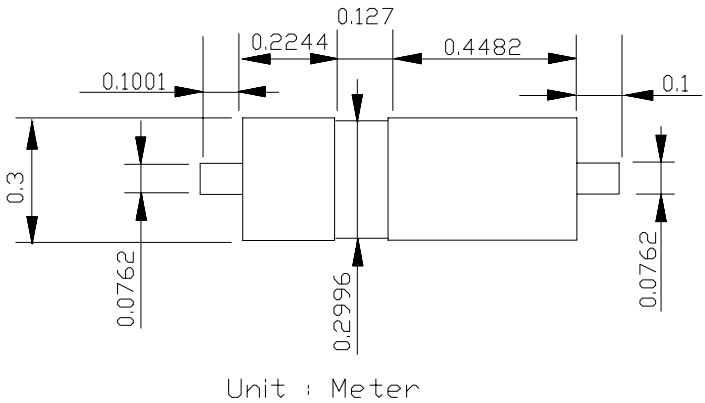

Figure 13. Optimal shape of muffler with respect to the best design set
Boundary Constraints: D_o=0.3 (m), L_o=1.0 (m)

Table 1. Optimal result in dealing with pure tone noise of 500 Hz

Common parameters			Control parameters			Results								Elapsed time
popuSize	*gen_no*	*bit_n*	*pc*	*pm*	*elt_no*	D_1(m)	D_3(m)	D_5(m)	L_1(m)	L_3(m)	L_5(m)	rt_1	*SPL*	t(Min.)
60	500	40	0.8	0.05	1	0.0762	0.0764	0.2998	0.1004	0.1001	0.1037	0.5112	27.18	1.06

Table 2. Comparison of results for the variations of control parameters

	Common parameters			Control parameters			Results								Elapsed time
	popuSize	*gen_no*	*bit_n*	*pc*	*pm*	*elt_no*	D_1(m)	D_3(m)	D_5(m)	L_1(m)	L_3(m)	L_5(m)	rt_1	*SPL*	t(Min.)
Case1	60	500	40	0.8	0.05	1	0.0762	0.2998	0.0762	0.1001	0.1717	0.1000	1.2283	93.6	3.30
Case2	60	500	40	0.8	0.05	0	0.0792	0.2811	0.0771	0.1011	0.1349	0.1315	0.7588	95.0	3.41
Case3	60	500	40	0.8	0	1	0.0762	0.2930	0.0763	0.1467	0.1269	0.1019	0.7832	94.5	3.40
Case4	60	500	40	0	0.05	1	0.0836	0.2597	0.0767	0.1540	0.1848	0.1006	1.5509	95.5	3.25

Table 3. Results for multiple running (different random initial populations)

iteration	Results								Elapsed time
	D_1(m)	D_3(m)	D_5(m)	L_1(m)	L_3(m)	L_5(m)	rt_1	*SPL*	t(Min.)
1st	0.0762	0.2997	0.0762	0.1002	0.1659	0.1008	1.3025	93.64	3.44
2nd	0.0762	0.2993	0.0763	0.1000	0.1772	0.1001	1.2169	93.65	3.38
3rd	0.0762	0.2996	0.0762	0.1001	0.1273	0.1000	1.9970	93.60	3.40
4th	0.0766	0.2999	0.0762	0.1017	0.1763	0.1001	1.2576	93.70	3.39
5th	0.0762	0.2998	0.0762	0.1008	0.1035	0.1001	1.9933	93.62	3.37
6th	0.0762	0.2987	0.0762	0.1002	0.1296	0.1004	1.9511	93.61	3.38
7th	0.0762	0.2960	0.0762	0.1003	0.1725	0.1004	1.3090	93.66	3.39
8th	0.0765	0.2999	0.0762	0.1032	0.1601	0.1006	1.2692	93.73	3.32
9th	0.0762	0.2927	0.0762	0.1001	0.1001	0.1015	1.5875	93.70	3.42
10th	0.0763	0.2982	0.0762	0.1001	0.1045	0.1000	1.9987	93.62	3.40
Average (1~10)	0.0762	0.2983	0.0762	0.1006	0.1417	0.1004	1.5882	93.61	
Best (3rd)	0.0762	0.2996	0.0762	0.1001	0.1273	0.1000	1.9970	93.60	3.40

Note : *popuSize*=60; *gen_no*=500; *bit_n*=40; *pc*=0.8; *pm*=0.05; *elt_no*=1

NOMENCLATURE

bit_n	bit length
c_o	sound speed (m s^{-1})
D_i	diameter of the *i*-th segment of straight duct (m)
elt_no	selection of elite (1 for yes and 0 for no)
f	frequency (Hz)
gen_no	maximum no. of generation
j	imaginary unit ($\sqrt{-1}$)
k	wave number.(ω / c_o)
L_i	length of the *i*-th segment of straight duct (m)
M_i	mean flow Mach number at the *i*-th segment of straight duct
pc	crossover ratio
p_i	pressure; acoustic pressure at the *i*-th point(Pa)
pm	mutation ratio
popuSize	no. of population
Q	volume flow rate of venting gas (m^3 s^{-1})
rt_1	GA's design parameter (L_4/L_2)
S_i	section area at the *i*-th point (m^2)
SPL_o	sound pressure level at the silencer inlet (dB)
SPL_T	sound pressure level at the silencer outlet (dB)
STL	sound transmission loss (dB)
u_i	acoustic particle velocity at the *i*-th point (m s^{-1})
ρ_o	air density (kg m^{-3})