SHAPE OPTIMIZATION OF MULTI-CHAMBER SIDE INLET/OUTLET MUFFLERS HYBRIDIZED WITH MULTIPLE PERFORATED INTRUDING TUBES USING A GENETIC ALGORITHM

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Key words: perforated intruding tube, decoupled numerical method, space constraints, genetic algorithm.

ABSTRACT

The use of perforated-tube side mufflers for depressing venting noise within a constrained space has been prevalent in modern industries. Also, research on mufflers equipped with side inlets/outlets has been thoroughly documented. However, research on shape optimization of side inlet/outlet mufflers hybridized with multiple open-ended perforated intruding tubes which may enhance acoustic performance has gone unnoticed. Therefore, we wish to not only analyze the sound transmission loss (STL) of side inlet/outlet mufflers but also to optimize their best design shape within a limited space.

In this paper, the generalized decoupling technique and the plane wave theory used in solving the coupled acoustical problem are employed. Also, a four-pole system matrix for evaluating acoustic performance is deduced in conjunction with a genetic algorithm (GA). We have also introduced a numerical study that deals with broadband noise within a constrained blower room using three kinds of mufflers. Additionally, before muffler shape optimization is performed, an accuracy check on the mathematical models has been performed. Moreover, to verify the reliability of the GA optimization, optimal noise abatements for various pure tones on various mufflers have been examined. Results reveal that mufflers equipped with perforated intruding tubes are superior to those equipped with non-perforated intruding tubes. Also, mufflers with multi-perforated tubes will increase the acoustic performance. Consequently, the approach used in seeking the optimal design of the STL proposed in this study is quite effective.

I. INTRODUCTION

Research on mufflers was started by Davis et al. in 1954 [5]. A side inlet/outlet muffler is customarily used [9] when dealing with horizontal industrial noise emitted from a perpendicular vertical system in the low frequency range. Because the constrained problem is mostly concerned with the necessity of operation and maintenance in practical engineering work, there is a growing need to optimize acoustical performance within a limited space. In previous work, the shape optimization of mufflers equipped with an internal non-perforated tube has been discussed [1, 3, 11, 22]. However, the acoustical performance is still insufficient.

Based on the coupled equations, an assessment of a new acoustical element (internal perforated tube) which will improve the acoustical performance for mufflers was discussed by Sullivan and Crocker in 1978 [18]. A series of theory and numerical techniques in decoupling the acoustical problems have been proposed [14-17, 19]. In 1981, Jayaraman and Yam [7] developed a method for finding an analytical solution; however, a presumption of the velocity equality within the inner and outer duct, which is not reasonable in the real world, is required. To overcome this drawback, Munjal et al. [12] provided a generalized de-coupling method. Regarding the flowing effect, Peat [13] publicized the numerical de-coupling method by finding the eigen value in transfer matrices. In order to maintain a steady volume-flow-rate in a venting system, a muffler’s back pressure within an allowable range is compulsory. Therefore, Wang [20] developed an open-ended perforated intruding-tube muffler, a low back-pressure muffler with non-plug tubes inside the cavity, using the BEM (Boundary Element Method). However, the need to investigate the optimal muffler design under space constraints was neglected.

To increase acoustical performance, three kinds of five-chamber side inlet mufflers (a muffler hybridized with four...
perforated intruding tubes, a muffler hybridized with two perforated tubes and two non-perforated tubes, and a muffler hybridized with four non-perforated tubes) with lower back pressure are adopted. A shape optimization of five-chamber side inlet mufflers that deal with broadband noise within a constrained blower room has been investigated by using a four-pole system matrix in conjunction with a decoupled numerical method. Moreover, a genetic algorithm (GA), a robust scheme used to search for the global optimum by imitating a genetic evolutionary process, has been used during the optimization process. Before the shape optimization of the mufflers, a reliability check of the GA optimization for various pure tones (300 Hz, 600 Hz, and 900 Hz) on various mufflers is performed.

II. THEORETICAL BACKGROUND

In this paper, three kinds of five-chamber side inlet/outlet mufflers (hybridized with four perforated intruding tubes, two perforated + two non-perforated tubes, and four non-perforated intruding tubes) were adopted for noise abatement on the constrained blower room shown in Fig. 1. The outlines of these mufflers as noise-reduction devices are shown in Figs. 2(a), 2(b), and 2(c). The acoustical fields with respect to various mufflers are shown in Figs. 3(a), 3(b) and 3(c).

As indicated in Figs. 2(a) and 3(a), the five-chamber side inlet/outlet muffler equipped with four perforated intruding tubes, which is composed of twenty-one acoustical elements, has seven categories of components — eleven straight ducts (I), two side-inlet tubes (II), two side-outlet tubes (III), one simple contracted element (IV), one simple expanded element (V), one expanded perforated intruding tube (VI), and one contracted perforated intruding tube (VII). As indicated in Figs. 2(b) and 3(b), the five-chamber side inlet/outlet muffler equipped with two perforated intruding tubes and two non-perforated intruding tubes has nine categories of components — eleven straight ducts (I), two side-inlet tubes (II), two side-outlet tubes (III), one simple contracted element (IV), one simple expanded element (V), one expanded perforated intruding tube (VI), one contracted perforated intruding tube (VII), one contracted non-perforated intruding tube (VIII), and one expanded non-perforated intruding tube (IX). Moreover, for a muffler equipped with four non-perforated intruding tubes, there are nine categories of components — eleven...
A Side Inlet/Outlet Muffler Hybridized with Four Perforated Intruding Tubes; (a) four perforated intruding tubes; (b) two perforated and two non-perforated intruding tubes; (c) four non-perforated intruding tubes.

The total transfer matrix assembled by multiplication is simplified as

\[ \left\{ \frac{p_i}{\rho_i c_i u_i} \right\} = \Pi_{n} T_n(f) \left[ \frac{p_{22}}{\rho_{22} c_{22} u_{22}} \right] \]  

(3)

The sound transmission loss (STL) of a muffler is defined as [10]

\[ \text{STL} = 20 \log \left( \frac{T_{11} + T_{12} + T_{21} + T_{22}}{2} \right) + 10 \log \left( \frac{S_1}{S_{21}} \right) \]  

(4a)

where

\[ L_{22} = A_{f_1}; L_{23} = A_{f_2}; L_{3} = A_{f_3}; \] \[ L_{A1} = A_{f_5} S(L_{23} - L_3)/2; \] \[ L_{A2} = A_{f_6} d_{h1} = A_{f_6}; sgm_1 = A_{f_6}; dh_1 = A_{f_6}; sgm_2 = A_{f_6} d_{h2} = A_{f_6}; \] \[ sgm_3 = A_{f_6} d_{h3} = A_{f_6}; sgm_4 = A_{f_6}; D_2 = A_{f_6} S L_2; D_3 = A_{f_6} S d_6; \] \[ D_4 = D_5 = A_{f_6} S L_4; D_6 = A_{f_6} \]  

(4b)

1. A Side Inlet/Outlet Muffler Hybridized with Four Perforated Intruding Tubes

As derived in previous work [1, 3, 10-13, 18, 22], individual transfer matrices with respect to straight ducts, side inlet/outlet tubes, simple expansion/contracted tubes, and perforated expanded/contracted intruding tubes are described as follows:

\[ \left[ \begin{array}{c} p_i \\ \rho_i c_i u_i \end{array} \right] = \left[ \begin{array}{cc} T_{i} \end{array} \right]_{j} T_{i} \left[ \begin{array}{c} p_{j+1} \\ \rho_{j+1} c_{j+1} u_{j+1} \end{array} \right] \]  

(1a)

where

\[ i: \text{ odd number at } 1, 3, 5, \ldots, 21 \]  

(1b)

\[ \left[ \begin{array}{c} p_j \\ \rho_j c_j u_j \end{array} \right] = \left[ \begin{array}{cc} T_{j} \end{array} \right]_{i} T_{j} \left[ \begin{array}{c} p_{j+1} \\ \rho_{j+1} c_{j+1} u_{j+1} \end{array} \right] \]  

(2a)

where

\[ j: \text{ even number at } 2, 4, 6, \ldots, 20 \]  

(2b)

2. A Side Inlet/Outlet Muffler Hybridized with Two Perforated Intruding Tubes and Two Non-Perforated Intruding Tubes

Similarly, as indicated in section II.1, the total transfer matrix assembled by multiplication is

\[ \left\{ \frac{p_i}{\rho_i c_i u_i} \right\} = \Pi_{n} T_n(f) \left[ \frac{p_{22}}{\rho_{22} c_{22} u_{22}} \right] \]  

(5)
The sound transmission loss (STL) of a muffler is defined as [10]

\[
STL(Q, f, Af_1, Af_2, Af_3, Af_4, Af_5, Af_6, Af_7, Af_8, Af_9, Af_{10})
\]

\[
= 20 \log \left( \frac{T_{11}^{\text{in}} + T_{12}^{\text{in}} + T_{21}^{\text{in}} + T_{22}^{\text{in}}}{T_{21}^{\text{in}}} \right) + 10 \log \left( \frac{S_1}{S_2} \right)
\]

(6a)

where

\[
L_{z_2} = Af_1; L_{z_3} = Af_2; L_1 = Af_3; L_2 = Af_4*L_{z_2}; L_3 = Af_5*L_{z_2};
\]

\[
L_5 = Af_6; dh_1 = Af_7; sgm_1 = Af_8; dh_2 = Af_9; sgm_2 = Af_9;
\]

\[
D_2 = Af_{11}*L_{z_5}; D_3 = Af_{12}*L_{z_5}; D_4 = Af_{13}*L_{z_5}; D_5 = Af_{14}*L_{z_5};
\]

\[
D_6 = Af_{15}
\]

(6b)

3. A Side Inlet/Outlet Muffler Hybridized with Four Non-Perforated Intruding Tubes

Likewise, as indicated in section 2.1, the total transfer matrix assembled by multiplication is

\[
\left( \begin{array}{c}
\rho_1 \\
\rho_2 \\
\rho_3 \\
\rho_4 \\
\rho_5 \\
\rho_6 \\
\rho_7 \\
\rho_8 \\
\rho_9 \\
\rho_{10} \\
\end{array} \right) = \left( \begin{array}{c}
T_1(f) \\
T_2(f) \\
T_3(f) \\
T_4(f) \\
T_5(f) \\
T_6(f) \\
T_7(f) \\
T_8(f) \\
T_9(f) \\
T_{10}(f) \\
\end{array} \right)
\]

(7)

The sound transmission loss (STL) of a muffler is defined as [10]

\[
STL(Q, f, Af_1, Af_2, Af_3, Af_4, Af_5, Af_6, Af_7, Af_8, Af_9, Af_{10})
\]

\[
= 20 \log \left( \frac{T_{11}^{\text{in}} + T_{12}^{\text{in}} + T_{21}^{\text{in}} + T_{22}^{\text{in}}}{T_{21}^{\text{in}}} \right) + 10 \log \left( \frac{S_1}{S_2} \right)
\]

(8a)

where

\[
L_{z_2} = Af_1; L_{z_3} = Af_2; L_1 = Af_3; L_2 = Af_4*L_{z_2}; L_3 = Af_5*L_{z_2};
\]

\[
D_2 = Af_{11}*L_{z_5}; D_3 = Af_{12}*L_{z_5}; D_4 = Af_{13}*L_{z_5}; D_5 = Af_{14}*L_{z_5}; D_6 = Af_{15}
\]

(8b)

4. Objective Function

By using the formulas of Eqs. (4) (6) (8), the objective function used in the GA optimization with respect to each type of muffler was established. For a five-chamber side inlet/outlet muffler hybridized with four perforated intruding tubes, the objective function in maximizing the STL at a pure tone (f) is

\[
OBJ_{11} = STL(Q, f, Af_1, Af_2, Af_3, Af_4, Af_5, Af_6, Af_7, Af_8, Af_9, Af_{10})
\]

(9)

The objective function in minimizing the broadband STL is

\[
OBJ_{21} = STL(Q, f, Af_1, Af_2, Af_3, Af_4, Af_5, Af_6, Af_7, Af_8, Af_9, Af_{10})
\]

(10a)

where

\[
OBJ_{21} = STL(Q, f, Af_1, Af_2, Af_3, Af_4, Af_5, Af_6, Af_7, Af_8, Af_9, Af_{10})
\]

(11)

Similarly, the objective function in minimizing the broadband SWL is

\[
OBJ_{22} = SWL(Q, f, Af_1, Af_2, Af_3, Af_4, Af_5, Af_6, Af_7, Af_8, Af_9, Af_{10})
\]

(12)

For a five-chamber side inlet/outlet muffler hybridized with four non-perforated intruding tubes, the objective function in maximizing the STL at a pure tone (f) is

\[
OBJ_{31} = STL(Q, f, Af_1, Af_2, Af_3, Af_4, Af_5, Af_6, Af_7, Af_8, Af_9, Af_{10})
\]

(13)

Likewise, the objective function in minimizing the broadband SWL is

\[
OBJ_{32} = SWL(Q, f, Af_1, Af_2, Af_3, Af_4, Af_5, Af_6, Af_7, Af_8, Af_9, Af_{10})
\]

(14)

The related ranges of parameters with respect to three kinds of mufflers are shown in Table 1.

III. MODEL CHECK

Before performing the GA optimal simulation on mufflers, an accuracy check of the mathematical models on three kinds of fundamental acoustical elements that include (1)
Table 1. Range of design parameters for three kinds of side inlet/outlet mufflers hybridized with perforated/non-perforated intruding tubes.

<table>
<thead>
<tr>
<th>Muffler type</th>
<th>Range of design parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>muffler (A)</td>
<td>( L_o = 1.4 \text{ (m)}; \ D_o = 0.7 \text{ (m)}; \ Q = 0.02 \text{ (m}^3/\text{s}) ); ( D_1 = 0.0508 \text{ (m)} ); ( A_{f1} = [0.5, 0.8] ); ( A_{f2} = [0.1, 0.2] ); ( A_{f3} = [0.08, 0.2] ); ( A_{f4} = [0.1, 0.9] ); ( A_{f5} = [0.2, 0.3] ); ( A_{f6} = [0.00175, 0.007] ); ( A_{f7} = [0.00175, 0.007] ); ( A_{f8} = [0.2, 0.9] ); ( A_{f9} = [0.00175, 0.007] ); ( A_{f10} = [0.03, 0.1] ); ( A_{f11} = [0.2, 0.9] ); ( A_{f12} = [0.03, 0.1] ); ( A_{f13} = [0.00175, 0.007] ); ( A_{f14} = [0.03, 0.1] ); ( A_{f15} = [0.2, 0.9] ); ( A_{f16} = [0.03, 0.1] ); ( A_{f17} = [0.2, 0.9] ); ( A_{f18} = [0.0508, 0.1] )</td>
</tr>
<tr>
<td>muffler (B)</td>
<td>( L_o = 1.4 \text{ (m)}; \ D_o = 0.7 \text{ (m)}; \ Q = 0.02 \text{ (m}^3/\text{s}) ); ( D_1 = 0.0508 \text{ (m)} ); ( A_{f1} = [0.5, 0.8] ); ( A_{f2} = [0.1, 0.2] ); ( A_{f3} = [0.08, 0.2] ); ( A_{f4} = [0.1, 0.9] ); ( A_{f5} = [0.2, 0.3] ); ( A_{f6} = [0.2, 0.9] ); ( A_{f7} = [0.00175, 0.007] ); ( A_{f8} = [0.00175, 0.007] ); ( A_{f9} = [0.2, 0.9] ); ( A_{f10} = [0.03, 0.1] ); ( A_{f11} = [0.2, 0.9] ); ( A_{f12} = [0.2, 0.9] ); ( A_{f13} = [0.2, 0.9] ); ( A_{f14} = [0.2, 0.9] ); ( A_{f15} = [0.0508, 0.1] )</td>
</tr>
<tr>
<td>muffler (C)</td>
<td>( L_o = 1.4 \text{ (m)}; \ D_o = 0.7 \text{ (m)}; \ Q = 0.02 \text{ (m}^3/\text{s}) ); ( D_1 = 0.0508 \text{ (m)} ); ( A_{f1} = [0.5, 0.8] ); ( A_{f2} = [0.1, 0.2] ); ( A_{f3} = [0.08, 0.2] ); ( A_{f4} = [0.1, 0.9] ); ( A_{f5} = [0.2, 0.3] ); ( A_{f6} = [0.2, 0.9] ); ( A_{f7} = [0.2, 0.9] ); ( A_{f8} = [0.2, 0.9] ); ( A_{f9} = [0.2, 0.9] ); ( A_{f10} = [0.0508, 0.1] )</td>
</tr>
</tbody>
</table>

Fig. 4. Performance of a one-chamber muffler equipped with perforated intruding tubes (Experimental data is from Wang et al. [21]).

single-chamber muffler equipped with two perforated intruding tubes, (2) a single-chamber muffler hybridized with two non-perforated intruding tubes, and (3) a side inlet/outlet single-chamber muffler are performed using the experimental data from Wang et al. [21], Chang et al. [2], and Chiu et al. [4]. As depicted in Figs. 4–6, the theoretical and experimental data for the models are accurate and in agreement. Therefore, the proposed fundamental mathematical models with related acoustical components are acceptable. Consequently, the models linked with the numerical method are applied to the shape optimization of five-chamber side inlet/outlet mufflers hybridized with perforated/non-perforated intruding tubes.

**IV. CASE STUDIES**

The noise reduction of a space-constrained blower room is shown in Fig. 1. The sound power levels (SWLs) of the blower

Fig. 5. Performance of a single-chamber muffler with extended tubes at the mean flow velocity of 3.4 m/sec (Experimental data is from Chang et al. [2]).

Fig. 6. Performance of single-chamber muffler with a side inlet/outlet for a stationary medium (Experimental data is from Chiu et al. [4]).
in lower frequencies (125 Hz, 250 Hz, 500 Hz, and 1000 Hz) at the pipe outlet of are listed in Table 2. To reduce the venting noise emitted from the blower’s outlet, three kinds of low back-pressure multi-chamber mufflers — five-chamber side inlet/outlet mufflers hybridized with perforated/non-perforated intruding tubes shown in Figs. 2(a), 2(b), and 2(c) — are considered. As shown in Fig. 1, the available space for a muffler is 0.7 m in width, 0.7 m in height, and 1.4 m in length. Before the minimization of the blower’s broadband noise is performed, a reliability check of the muffler is 0.7 m in width, 0.7 m in height, and 1.4 m in length. The related flow rate ($Q$) and thickness of a perforated tube ($t$) are preset as 0.02 (m$^3$/s) and 0.001 (m), respectively. The corresponding $OBJ$ functions, space constraints, and the ranges of design parameters are summarized in Table 1.

### V. GENETIC ALGORITHM CASE STUDIES

For the optimization of the objective function ($OBJ$), the design parameters of ($X_1$, $X_2$, ..., $X_i$) were determined [6, 8]. When the $bit$ (the bit length of the chromosome) was chosen, the interval of the design parameter ($X_i$) with $[L_b, U_b]_k$ was then mapped to the band of the binary value. The mapping system between the variable interval of $[L_b, U_b]_k$ and the $k^{th}$ binary chromosome of

$$[0 0 0 0 \cdot \cdot \cdot 0 0 0 1 1 1 \cdot \cdot \cdot 1 1 1]$$

was then built. The encoding from $x$ to $B2D$ (binary to decimal) was performed as

$$B2D_k = \text{integer} \left( \frac{x_k - L_b}{U_b - L_b} (2^{bit} - 1) \right)$$  \hspace{1cm} (15)

The initial population was built up by randomization. The parameter set was encoded to form a string which represented the chromosome. By evaluating the objective function ($OBJ$), the whole set of chromosomes $[B2D_1, B2D_2, ..., B2D_i]$ that changed from binary form to decimal form was then assigned a fitness by decoding the transformation system

$$fitness = OBJ(X_1, X_2, ..., X_i)$$  \hspace{1cm} (16a)

where

$$X_i = B2D_i * (U_b - L_b)/(2^{bit} - 1) + L_b$$  \hspace{1cm} (16b)

The flow diagram during a muffler’s shape optimization is depicted in Fig. 7.

As indicated in Fig. 7, to process the elitism of a gene, the tournament selection, a random comparison of the relative fitness of pairs of chromosomes, was applied. During the GA optimization, one pair of offspring from the selected parent was generated by a uniform crossover with a probability of $pc$. Genetically, a mutation occurred with a probability of $pm$ where the new and unexpected point was brought into the GA optimizer’s search domain. To prevent the best gene from disappearing and to improve the accuracy of optimization during reproduction, an elitism scheme of keeping the best gene (one pair) in the parent generation with the tournament strategy was developed.

The process was terminated when a number of generations exceeded a pre-selected value of $gen$. The operations in the GA method are pictured in Fig. 8.
Table 3. Comparison of results for the variations of control parameters-pop, gen, bit, pc, pm in a five-chamber side inlet/outlet muffler equipped with two perforated intruding tubes and two non-perforated intruding tubes (muffler (B)) (target tone: 300 Hz).

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<th>pop</th>
<th>gen</th>
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<th>pc</th>
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<td>14</td>
<td>0.7455</td>
<td>0.1723</td>
<td>0.1626</td>
<td>0.2384</td>
<td>0.2123</td>
<td>0.2205</td>
<td>0.004957</td>
<td>0.09767</td>
</tr>
</tbody>
</table>
Table 4. Optimal design parameters and STLs for three kinds of mufflers (muffler (A), muffler (B), and muffler (C)) at targeted tone (300 Hz).

<table>
<thead>
<tr>
<th>Muffler type</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
<th>A5</th>
<th>A6</th>
<th>A7</th>
<th>A8</th>
<th>STL(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muffler (A)</td>
<td>0.6686</td>
<td>0.1317</td>
<td>0.1416</td>
<td>0.1782</td>
<td>0.5411</td>
<td>0.2903</td>
<td>0.00590</td>
<td>0.08659</td>
<td>0.00352</td>
</tr>
<tr>
<td>Muffler (B)</td>
<td>0.05285</td>
<td>0.00271</td>
<td>0.0968</td>
<td>0.00667</td>
<td>0.03123</td>
<td>0.5428</td>
<td>0.4381</td>
<td>0.6133</td>
<td>0.09178</td>
</tr>
<tr>
<td>Muffler (C)</td>
<td>0.7633</td>
<td>0.1701</td>
<td>0.1479</td>
<td>0.2713</td>
<td>0.2214</td>
<td>0.3841</td>
<td>0.4251</td>
<td>0.4142</td>
<td>0.4073</td>
</tr>
</tbody>
</table>

**VI. RESULTS AND DISCUSSION**

1. Results

To achieve an acceptable optimization, five kinds of optimal GA parameters, including population size (pop), chromosome length (bit), maximum generation (gen), crossover ratio (pc), and mutation ratio (pm), are obtained by varying their values during optimization. The results of shaped mufflers at various targeted tones are described below.

1) Pure Tone Noise Optimization

A. Pure Tone Noise Optimization at 300 Hz (muffler (A), muffler (B), and muffler (C))

For a five-chamber side inlet/outlet muffler equipped with two perforated and two non-perforated intruding tubes (muffler (B)), various sets of GA parameters are tested by using the formulas of Eq. (31) during the optimal process. The resultant simulated result optimized with respect to the pure tone of 300 Hz is shown in Table 3. As indicated in Table 3, the optimal design data can be obtained when the GA parameters at pop, bit, gen, pc, and pm = 120, 20, 100, 0.8, 0.05 are applied. The optimal STLs with respect to various GA parameters (pop, bit, gen, pc, and pm) are plotted in Figs. 9 and 10. By using the above GA parameters, the optimal muffler’s design data for two kinds of side inlet/outlet mufflers (muffler (A) and muffler (C)) used to maximize the mufflers’ sound transmission loss at 300 Hz is performed. The optimal design parameters and STLs are summarized in Table 4. Three optimal STLs with respect to various mufflers (muffler (A), muffler (B), and muffler (C)) are plotted in Fig. 11.

B. Pure Tone Noise Optimization at 600 Hz and 900 Hz (muffler (B) and muffler (C))

Using the formulas of Eq. (33) and the above GA parameter set in muffler (B), the optimized design data at the targeted tones (600 Hz and 900 Hz) are performed. The resultant data with respect to three tones is summarized in Table 5. Using the optimal design in a theoretical calculation, three optimal STL curves with respect to the targeted frequencies are plotted and depicted in Fig. 12. Moreover, using the formulas of
Table 5. Optimal design parameters and STLs at three tones (300 Hz, 600 Hz, and 900 Hz) (muffler (B)).

<table>
<thead>
<tr>
<th>Targeted tone (Hz)</th>
<th>Design parameters</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_{f_1}$</td>
<td>$A_{f_2}$</td>
</tr>
<tr>
<td>300</td>
<td>0.7455</td>
<td>0.1723</td>
</tr>
<tr>
<td></td>
<td>$A_{f_9}$</td>
<td>$A_{f_10}$</td>
</tr>
<tr>
<td></td>
<td>0.006661</td>
<td>0.0313</td>
</tr>
<tr>
<td>600</td>
<td>0.5865</td>
<td>0.1108</td>
</tr>
<tr>
<td></td>
<td>$A_{f_9}$</td>
<td>$A_{f_10}$</td>
</tr>
<tr>
<td></td>
<td>0.003854</td>
<td>0.08734</td>
</tr>
<tr>
<td>900</td>
<td>0.7871</td>
<td>0.1499</td>
</tr>
<tr>
<td></td>
<td>$A_{f_9}$</td>
<td>$A_{f_10}$</td>
</tr>
<tr>
<td></td>
<td>0.00524</td>
<td>0.0794</td>
</tr>
</tbody>
</table>

Table 6. Optimal design parameters and STLs at three tones (300 Hz, 600 Hz, and 900 Hz) (muffler (C)).

<table>
<thead>
<tr>
<th>Targeted tone (Hz)</th>
<th>Design parameters</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_{f_1}$</td>
<td>$A_{f_2}$</td>
</tr>
<tr>
<td>300</td>
<td>0.7633</td>
<td>0.1701</td>
</tr>
<tr>
<td></td>
<td>$A_{f_9}$</td>
<td>$A_{f_10}$</td>
</tr>
<tr>
<td></td>
<td>0.3841</td>
<td>0.4251</td>
</tr>
<tr>
<td>600</td>
<td>0.6308</td>
<td>0.1162</td>
</tr>
<tr>
<td></td>
<td>$A_{f_9}$</td>
<td>$A_{f_10}$</td>
</tr>
<tr>
<td></td>
<td>0.6468</td>
<td>0.3553</td>
</tr>
<tr>
<td>900</td>
<td>0.5387</td>
<td>0.1540</td>
</tr>
<tr>
<td></td>
<td>$A_{f_9}$</td>
<td>$A_{f_10}$</td>
</tr>
<tr>
<td></td>
<td>0.3225</td>
<td>0.2479</td>
</tr>
</tbody>
</table>

Fig. 11. Comparison of STLs with respect to three kinds of side inlet/outlet mufflers at the target tone of 300 Hz (A: four perforated intruding tubes ($f_c = 996$ Hz); B: two perforated and two non-perforated intruding tubes ($f_c = 996$ Hz); C: four non-perforated intruding tubes ($f_c = 996$ Hz)).

Eq. (35) and the same GA parameters in optimizing muffler (C) at the targeted tones (600 Hz and 900 Hz), the resultant data with respect to three tones is summarized in Table 6. Also, using the optimal design in a theoretical calculation, three optimal STL curves with respect to targeted frequencies are plotted and depicted in Fig. 13.
Table 7. Optimal design parameters and SWL<sub>T</sub> for three kinds of mufflers (muffler (A), muffler (B), and muffler (C)) (broadband noise).

<table>
<thead>
<tr>
<th>Muffler type</th>
<th>Design parameters</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muffler (A)</td>
<td>( A_1 ), ( A_2 ), ( A_3 ), ( A_4 ), ( A_5 ), ( A_6 ), ( A_7 ), ( A_8 ), ( A_{\text{SWL}} ), ( A_{\text{T}} )</td>
<td>( \text{SWL}_T ) (dB)</td>
</tr>
<tr>
<td></td>
<td>0.6334, 0.1233, 0.1010, 0.3956, 0.7475, 0.2242, 0.00415, 0.07872, 0.00327</td>
<td>35.8</td>
</tr>
<tr>
<td>Muffler (B)</td>
<td>( A_1 ), ( A_2 ), ( A_3 ), ( A_4 ), ( A_5 ), ( A_6 ), ( A_7 ), ( A_8 ), ( A_{\text{SWL}} ), ( A_{\text{T}} )</td>
<td>( \text{SWL}_T ) (dB)</td>
</tr>
<tr>
<td></td>
<td>0.6909, 0.1441, 0.1471, 0.2693, 0.5016, 0.2636, 0.00470, 0.07631, 59.3</td>
<td></td>
</tr>
<tr>
<td>Muffler (C)</td>
<td>( A_1 ), ( A_2 ), ( A_3 ), ( A_4 ), ( A_5 ), ( A_6 ), ( A_7 ), ( A_8 ), ( A_{\text{SWL}} ), ( A_{\text{T}} )</td>
<td>( \text{SWL}_T ) (dB)</td>
</tr>
<tr>
<td></td>
<td>0.6932, 0.1285, 0.1488, 0.2235, 0.2851, 0.2928, 0.7803, 0.5866, 66.2</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 13. Comparison of STLs with respect to three targeted tones (300 Hz, 600 Hz, and 900 Hz) (muffler (C); \( f_c = 996 \) Hz).

2) Broadband Noise Optimization

By using the formulas of Eqs. (32) (34) (36) and the GA parameters of \( \text{pop} = 120, \text{bit} = 20, \text{gen} = 100, \text{pc} = 0.8, \text{pm} = 0.05 \), three kinds of optimal design parameters for minimizing the sound power level at the muffler’s outlet within a limited space are shown in Table 7 and plotted in Fig. 14. The resultant sound power levels with respect to three kinds of mufflers have been dramatically reduced from 148.8 dB to 35.8 dB, 59.8 dB, and 66.2 dB.

2. Discussion

To achieve sufficient optimization, the selection of the appropriate GA parameter set is essential. As indicated in Table 3 and Figs. 9–10, the best GA sets with respect to muffler (B) — a five-chamber side inlet/outlet muffler equipped with two perforated and two non-perforated intruding tubes — at the targeted pure tone noise of 300 Hz are shown. Also, using the GA parameter set in various mufflers (muffler (A) and muffler (C)) and applying the optimal design in a theoretical calculation, three optimal STL curves with respect to various mufflers are obtained and shown in Fig. 11. Fig. 11 reveals that mufflers equipped with perforated intruding tubes (muffler (A) and muffler (B)) are superior to those equipped with non-perforated intruding tubes (muffler (C)). Moreover, mufflers with multi-perforated tubes will increase the acoustic performance at the targeted frequency.

As can be observed in Tables 5–6 and Figs. 12–13, the STLs are maximized at the desired frequencies (300 Hz, 600 Hz, and 900 Hz). Therefore, using the GA optimization to find a better design solution is seen to be reliable. In addition, it has been found that the acoustical performance for a side inlet/outlet muffler equipped with multi-perforated tubes is much better than mufflers equipped with non-perforated tubes. Moreover, the tuned tone band for a side inlet/outlet muffler equipped with multi-perforated tubes is much wider than mufflers equipped with non-perforated tubes. Also, the acoustical performance at a higher targeted tone will increase.

Additionally, in dealing with the broadband noise (125 Hz–1000 Hz) using the above mufflers, the GA’s solution shown in Table 7 and Fig. 14 can also provide the appropriate and sufficient sound reduction within a constrained space. As indicated in Table 7, the overall noise reductions with respect
to three kinds of mufflers (muffler (A), muffler (B), and muffler (C)) can reach 113 dB, 89 dB, and 82.6 dB. As shown in Fig. 14, the whole acoustical performance of muffler (A) is superior to that of other mufflers. It has been seen that the acoustical performance for a side inlet/outlet muffler equipped with multi-perforated tubes is much better than that of mufflers equipped with non-perforated tubes.

VII. CONCLUSION

It has been shown that five-chamber side inlet/outlet mufflers hybridized with perforated/non-perforated intruding-tubes in conjunction with a GA optimizer can be easily and efficiently optimized within a constrained space by using a generalized decoupling technique, a plane wave theory, as well as a four-pole transfer matrix. Five kinds of GA parameters (pop, bit, gen, pc, and pm) play essential roles in the solution’s accuracy during GA optimization. As indicated in Figs. 11–13, the tuning ability established by adjusting the design parameters of five-chamber side inlet/outlet mufflers hybridized with perforated/non-perforated intruding-tubes is reliable. Moreover, as indicated in Table 4 and Fig. 11, the acoustical performances of the mufflers having perforated intruding tubes (muffler (A) and muffler (B)) are higher than those having non-perforated intruding tubes (muffler (C)). It has also been found that the acoustic performance of the muffler will increase at the targeted frequency when the perforated tubes are increased.

As can be seen in Figs. 12–13, the tuned tone band for a side inlet/outlet muffler having more perforated tubes is much wider and higher than mufflers having non-perforated tubes. Simulated results indicate that the mufflers have better acoustical performance at a higher targeted tone compared to the lower targeted tones.

In addition, using the acoustical treatment in the broadband noise, the GA’s solution shown in Fig. 14 can also provide adequate noise reduction by adjusting the design data in conjunction with the GA optimizer. Table 7 reveals that the overall noise reductions with respect to three kinds of mufflers are 113 dB, 89 dB, and 82.6 dB. This means that the acoustical performance for a side inlet/outlet muffler having multi-perforated tubes is indeed superior to those mufflers having non-perforated tubes.

Consequently, the approach used for the optimal design of the side inlet/outlet mufflers equipped with multiple open-ended perforated/non-perforated intruding tubes proposed in this study is quite efficient in dealing with industrial venting noise within a constrained space.

NOMENCLATURE

This paper is constructed on the basis of the following notations:

- \( C_v \) sound speed (m s\(^{-1}\))
- \( d_h \) the diameter of a perforated hole on the i-th inner tube (m)
- \( D_i \) diameter of the i-th tubes (m)
- \( D_o \) diameter of the outer tube (m)
- \( elt \) elitism (1 for yes, 0 for no)
- \( f \) cyclic frequency (Hz)
- \( f_c \) cut-off frequency of plane wave (Hz)
- \( gen \) maximum iteration
- \( j \) imaginary unit
- \( k \) wave number (\( \frac{\omega}{c_o} \))
- \( L_i \) length of the i-th segment of a muffler (m)
- \( L_o \) total length of the muffler (m)
- \( M \) mean flow Mach number
- \( OBJ_i \) objective function (dB)
- \( pc \) crossover ratio
- \( pi \) acoustic pressure at the i-th node (Pa)
- \( pm \) mutation ratio
- \( pop \) number of population
- \( Q \) volume flow rate of venting gas (m\(^3\) s\(^{-1}\))
- \( S_i \) section area at the i-th node (m\(^2\))
- \( STL \) sound transmission loss (dB)
- \( SWLO_i \) the original SWL with respect to i-th octave band frequency at the inlet of the muffler (dB)
- \( [T_{m}(f)] \) components of four-pole transfer matrices for the m-th acoustical mechanism
- \( T'_{ij}, T''_{ij}, T'''_{ij} \) components of a four-pole transfer system matrices
- \( u_i \) acoustic particle velocity at the i-th node (m s\(^{-1}\))
- \( \rho_o \) air density (kg m\(^{-3}\))
- \( \rho_i \) acoustical density at the i-th node
- \( sgm_i \) the porosity of the i-th inner perforated tube.

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REFERENCES


