SHAPE OPTIMIZATION OF MULTI-CHAMBER PLENUMS WITH MULTI-LAYER SOUND ABSORBERS USING AN ARTIFICIAL IMMUNE METHOD

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Key words: multi-chamber plenum, multi-layer sound absorber, artificial immune method, optimization, space-constrained.

ABSTRACT

Because of the space constraints problem in practical engineering work, there is a growing need to optimize the acoustical performance of a sound-proofing device within a fixed space. The optimal mechanism used in adjusting either the plenum’s chamber or an internal sound absorber has been ignored. In order to maximize the acoustical performance of a plenum, a case study of depressing a diesel engine noise by using three kinds of optimally shaped multi-chamber acoustical plenums lined with three kinds of multi-layer sound absorbers is introduced. On the basis of constrained weight and space in the plenum, a low cost optimal acoustical mechanism was assessed using an artificial immune method (AIM).

Consequently, this paper provides a quick, economical, and effective method for reducing noise levels by optimally designing shaped multi-chamber acoustical plenums lined with multi-layer sound absorbers using an artificial immune method.

I. INTRODUCTION

Research on the acoustical plenum has been widely discussed. Ko [17] started the study of sound transmission loss (STL) for a rectangular tube that had both the upper and the lower sides lined with perforated sound absorbing material. Blair and Coates [3] assessed the STL of a venting system based on the linear acoustic theory. Later, a sound attenuation loss of a rectangular tube lined with sound absorbing material on two or four sides of the tube was proposed. [22]. At the same time, the influence of noise reduction with respect to different flow rates was also analyzed [10]. Afterward, a new technology to reduce the STL of a one-chamber plenum by lining the instrument with sound absorbing material was advanced [2]. Also, the acoustical performance of a side inlet/outlet plenum using a plane wave theory was suggested [25]. Moreover, the acoustical performance of a rectangular plenum using both theoretical and experimental data was analyzed [20]. Furthermore, the influence of a plenum’s acoustical performance with respect to the perforated hole’s distance using a finite element method was assessed [21].

There is a growing need to optimize the acoustical performance within a fixed space. However, the research work of optimally shaped multi-chamber acoustical plenum within a space-constrained situation has been overlooked. In order to efficiently maximize the acoustical performance of a multi-chamber plenum, a numerical assessment in finding three kinds of optimally shaped multi-chamber acoustical plenum (one-chamber, two-chamber, and three-chamber) lined with three kinds of multi-layer sound absorbers (one-layer, two-layer, and three-layer) utilizing an artificial immune method (AIM) will be presented. Here, to facilitate the numerical assessment, not only the theoretical formula [2] in predicting an acoustical plenum’s STL but also the formula in predicting the sound absorbing coefficient of a multi-layer sound absorber [6] will be linked and adopted in the mathematical model. Moreover, to maintain the lowest manufacturing cost in the plenum, the total thickness of the perforated plates and the sound absorbing material inside the sound absorber will be fixed in advance.

II. MATHEMATICAL MODELS

A multi-chamber acoustical plenum internally lined with multi-layer sound absorbers shown in Fig. 1 is adopted to reduce the noise emitted from a diesel engine. The mathematical model for the multi-chamber acoustical plenum is described below.

I. The One-chamber Acoustical Plenum

As indicated in Fig. 2, for a multi-chamber plenum inter-
M.-C. Chiu: Shape Optimization of Multi-Chamber Plenums by AIM

219

2000 cc 150 hp
2000 RPM

Fig. 1. The noise control of a diesel engine using a multi-chamber plenum lined with a multi-layer sound absorber.

\[ W_{df-i} = W_{IN-i} S_{e-i} \cos \vartheta_i / 2 \pi dd_i^2 \]  

(2)

Combining Eq. (1a) with Eq. (2), the total sound power \( W_{OUT-i} \) at the outlet of the \( i \)-th chamber plenum is

\[ W_{OUT-i} = W_{df-i} + W_{df-i} \]

\[ = W_{IN-i} \left( S_{e-i} / R_i + S_{e-i} \cos \vartheta_i / 2 \pi dd_i^2 \right) \]  

(3)

For a \( n \)-chamber plenum, the total sound power \( W_{OUT-n} \) at the outlet of the \( n \)-th chamber plenum is

\[ W_{OUT-n} = W_{df-n} + W_{df-n} \]

\[ = W_{IN-n} \left( S_{e-n} / R_n + S_{e-n} \cos \vartheta_n / 2 \pi dd_n^2 \right) \]  

(4)

where \( W_{IN-n} = W_{OUT-(n-1)} \)

Therefore, the substitution of \( W_{OUT-n} \) can be expressed as

\[ W_{OUT-n} = W_{IN-n} \left( S_{e-n} / R_n + S_{e-n} \cos \vartheta_n / 2 \pi dd_n^2 \right) \]

\[ = W_{IN-n} \sum_{i=1}^{n} \left( S_{e-i} / R_i + S_{e-i} \cos \vartheta_i / 2 \pi dd_i^2 \right) \]  

(5)

According the definition of sound transmission, the STL for an \( n \)-chamber plenum is

\[ STL_n (\bar{\chi}) = -10 \log_{10} \frac{W_{OUT-n}}{W_{IN-n}} \]

\[ = 10 \log_{10} \sum_{i=1}^{n} \left( \frac{1}{S_e \left( 1 - \bar{\alpha} \frac{1 - \cos \vartheta}{2 \pi dd_i^2} \right)} \right) \]  

(6a)

\[ \bar{\chi} = (\bar{\alpha} (f); S_{e-1}, S_{e-2}, S_{e-n}; S_{w-1}, S_{w-2}, \ldots, S_{w-n}; dd_1, dd_2, \ldots, dd_n) \]  

(6b)

where \( S_e \) is the outlet area, \( S_w \) is the total inner area of the plenum, \( \bar{\alpha} \) is the average sound absorption coefficient within a plenum, \( dd \) is the distance between the inlet and the outlet of the plenum, and \( \vartheta \) is the angle between the diagonal line (from plenum inlet to plenum outlet) and the horizontal line.

2. The Sound Absorption Coefficients for Multi-layer Sound Absorber

Four kinds of multi-layer sound absorbers (one-layer, two-layer, and three-layer) inside the inner wall of the plenum are shown in Fig. 3. The derivation of sound absorption coefficients with respect to the three kinds of multi-layer sound absorbers are described below.
1) A One-layer Sound Absorber

As indicated in Fig. 3(A), the acoustic impedance on the perforated front plate is obtained from the bottom wall where the value of the impedance is infinity. There are four points representing the absorbing impedance within the absorber. The absorber is composed of a structure of “rigid-backing plate + Li thickness of air + Di thickness of the acoustic fiber + qi thickness of the perforated front plate.” As derived in a previous study [6], for a wave propagating normally in a quiescent medium symbolized by “m,” the general matrix form between point i and point i+1 is expressed as

\[
\begin{pmatrix}
p_{i+1} \\
u_{i+1}
\end{pmatrix} =
\begin{pmatrix}
\cos(k_m L_i) & jZ_m \sin(k_m L_i) \\
jZ_m \sin(k_m L_i) & \cos(k_m L_i)
\end{pmatrix}
\begin{pmatrix}
p_i \\
u_i
\end{pmatrix}
\] (7)

Therefore, the relationship of the acoustic pressure \( p \) and the acoustic particle velocity \( u \) between point 0 and point 1 is expressed as the transfer matrix and shown below.

\[
\begin{pmatrix}
p_1 \\
u_1
\end{pmatrix} =
\begin{pmatrix}
\cos(\omega L_1/c_o) & j\rho_s c_o \sin(\omega L_1/c_o) \\
j\rho_s c_o \sin(\omega L_1/c_o) & \cos(\omega L_1/c_o)
\end{pmatrix}
\begin{pmatrix}
p_0 \\
u_0
\end{pmatrix}
\] (8)

Developing Eq. (8) yields

\[Z_1 = -j\rho_s c_o \cos\left(\frac{\omega L_1}{c_o}\right)\] (9)

The relationship of the acoustic pressure \( p \) and the acoustic particle velocity \( u \) with respect to points 1 and 2 is expressed in the transfer matrices below.

\[
\begin{pmatrix}
p_2 \\
u_2
\end{pmatrix} =
\begin{pmatrix}
\cos(k_{fiber-1} D_1) & jZ_{fiber-1} \sin(k_{fiber-1} D_1) \\
jZ_{fiber-1} \sin(k_{fiber-1} D_1) & \cos(k_{fiber-1} D_1)
\end{pmatrix}
\begin{pmatrix}
p_1 \\
u_1
\end{pmatrix}
\] (10)

By developing Eq. (10), an alternative form of Eq. (10) yields

\[
\begin{pmatrix}
p_2 \\
u_2
\end{pmatrix} = Z_{fiber-1} \begin{pmatrix}
\cosh(k_{fiber-1} D_1) + Z_{fiber-1} \sinh(k_{fiber-1} D_1) \\
\sinh(k_{fiber-1} D_1) + Z_{fiber-1} \cosh(k_{fiber-1} D_1)
\end{pmatrix}
\begin{pmatrix}
p_1 \\
u_1
\end{pmatrix}
\] (11)

By adopting the formula of the specific normal impedance and wave number [9], Eq. (11) is written as

\[
Z_2 = \left(R_{fiber-1} + jX_{fiber-1}\right)
\begin{pmatrix}
\sinh(k_{fiber-1} D_1) \cos(k_{fiber-1} D_1) - j\sin(k_{fiber-1} D_1) \\
\cos(k_{fiber-1} D_1) \cosh(k_{fiber-1} D_1) - j\sinh(k_{fiber-1} D_1)
\end{pmatrix}
\begin{pmatrix}
p_1 \\
u_1
\end{pmatrix}
\] (12)

For sound flowing into the perforated plate, it is assumed that the incident sound passes through the holes of the perforated plate and is immediately transmitted to the porous material behind the perforated plate [19, 24]. The continuity of the particle velocity is then applied and expressed as

\[u_2 = u_3\] (13)

Acoustic impedance yields

\[p_3 = Z_{p1} u_2 + p_2\] (14)

Combining Eqs. (13)–(14), the transfer matrix between point 2 and point 3 yields

\[
\begin{pmatrix}
p_3 \\
u_3
\end{pmatrix} =
\begin{pmatrix}
1 & Z_{p1} \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
p_2 \\
u_2
\end{pmatrix}
\] (15)
Developing Eq. (15) and substituting Eq. (7), the specific normal impedance at point 3 is

\[ Z_3 = Z_2 + Z_{pl} \]  

(16)

Adopting the specific normal impedance and wave number of the perforated plate [1] yields

\[ Z_{pl} = \frac{\rho_0}{\epsilon_1} \sqrt{8 \pi \omega} \left( 1 + \frac{q_1}{2d_1} \right) + j \frac{\omega \rho_0}{\epsilon_1} \left[ \sqrt{\frac{8 \pi}{\omega}} \left( 1 + \frac{q_1}{2d_1} \right) + q_1 + \delta_1 \right] \]

(17a)

\[ \delta_1 = 0.85(2d_1) \left( 1 - 1.47 \sqrt{\epsilon_1^2 + 0.47 \epsilon_1^2} \right) \]

(17b)

For normal incidence, the sound absorption coefficient [14, 19, 24] is

\[ \alpha_3(f, \epsilon_1, \epsilon_2, d_1, d_2, R_1, R_2, q_1, q_2, D_{f1}, D_{f2}, L_1, L_2, DD) \]

\[ = 1 - \left( \frac{Z_{pl} - \rho_c}{Z_3 + \rho_c} \right)^2 \]

(22)

3. Overall Silenced Sound Power Level

The silenced octave sound power level shown in Fig. 1 is

\[ SWL_i = SWLO_i - STL_i \]

(26)

where the SWLO\_i is the original SWL at the inlet of an acoustical plenum (or air compressor’s pipe outlet), and i is the index of the octave band frequency. The STL\_i is the muffler’s STL with respect to the relative octave band frequency. And, the SWL\_i is the silenced SWL at the outlet of a muffler with respect to the relative octave band frequency. Finally, the overall SWL silenced by a muffler at the outlet is
4. Objective Function

By using the formulas of Eqs. (6), (18), (22), (25), and (27), the objective function used in minimizing the broadband noise via the AIM technique was established. Moreover, an objective function used in a reliability check of the AIM method by maximizing the sound transmission loss of a one-chamber plenum lined with a one-layer sound absorber at a targeted tone of 3000 Hz was also constructed. To achieve a better acoustical performance with lower manufacturing cost, the total weight of sound absorbers was fixed.

1) Maximization of Sound Transmission Loss of a One-chamber Plenum lined with a One-layer Sound Absorber at a Pure Tone (f)

Combining Eq. (6) with Eq. (27), the objective function is

\[
OBJ_{111} = STL(x) \quad (28a)
\]

\[
x = (f, p_i, d_i, x, DD) \quad ; \quad (28b)
\]

2) SWL\(_\tau\) Minimization for a Broadband Noise

Combining Eq. (6) with Eq. (18) and Eq. (27), the objective function for a one-chamber plenum with a one-layer sound absorber is

\[
OBJ_{211} = SWL_{\tau}(\overline{X}) \quad (29a)
\]

\[
\overline{X} = (p_i, d_i, DD, x5, DD, x, DD) \quad ; \quad (29b)
\]

Combining Eq. (6) with Eq. (22) and Eq. (27), the objective function for a one-chamber plenum with a two-layer sound absorber is

\[
OBJ_{212} = SWL_{\tau}(\overline{XX}) \quad (30a)
\]

\[
\overline{XX} = (p_i, d_i, D_{j1}, DD, x5, DD, x, DD, DD) \quad ; \quad (30b)
\]

Combining Eq. (6) with Eq. (25) and Eq. (27), the objective function for a one-chamber plenum with a three-layer sound absorber is

\[
OBJ_{213} = SWL_{\tau}(\overline{XXX}) \quad (31a)
\]

\[
\overline{XXX} = (p_i, d_i, x3, DD, x5, x, DD, x, DD, DD) \quad ; \quad (31b)
\]

Similarly, the objective function for a two-chamber plenum with a one-layer sound absorber is

\[
OBJ_{221} = SWL_{\tau}(\overline{XX}) \quad (32a)
\]

\[
\overline{XX} = (p_i, d_i, DD, x1, x2) \quad ; \quad (32b)
\]

The objective function for a two-chamber plenum with a two-layer sound absorber is

\[
OBJ_{222} = SWL_{\tau}(\overline{XX}) \quad (33a)
\]

\[
\overline{XX} = (p_i, d_i, D_{j1}, DD, x5, p_i, d_i, x1, x2) \quad ; \quad (33b)
\]

The objective function for a two-chamber plenum with a three-layer sound absorber is

\[
OBJ_{231} = SWL_{\tau}(\overline{XXX}) \quad (34a)
\]

\[
\overline{XXX} = (p_i, d_i, x3, DD, x5, x, DD, x, DD, DD, DD, x, DD, DD) \quad ; \quad (34b)
\]

Likewise, the objective function for a three-chamber plenum with a one-layer sound absorber is

\[
OBJ_{231} = SWL_{\tau}(\overline{XX}) \quad (35a)
\]

\[
\overline{XX} = (p_i, d_i, x3, DD, x5, x, DD, DD, DD, DD, DD) \quad ; \quad (35b)
\]

Likewise, the objective function for a three-chamber plenum with a two-layer sound absorber is
Table 1. Spectrum of an original sound power level (SWLO) inside the outlet tube of the diesel engine.

<table>
<thead>
<tr>
<th>Frequency - Hz</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWL = 120 + 10log_{10} kw – ( lucr/1.2) – dB</td>
<td>140.2</td>
<td>140.2</td>
<td>140.2</td>
<td>140.2</td>
<td>140.2</td>
<td>140.2</td>
<td>140.2</td>
</tr>
<tr>
<td>Spectrum correction – dB</td>
<td>-3</td>
<td>-7</td>
<td>-15</td>
<td>-19</td>
<td>-25</td>
<td>-35</td>
<td></td>
</tr>
<tr>
<td>A-weighted</td>
<td>-16</td>
<td>-9</td>
<td>-3</td>
<td>0</td>
<td>+1</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>SWLO – dB(A)</td>
<td>121.2</td>
<td>124.2</td>
<td>122.2</td>
<td>121.2</td>
<td>116.2</td>
<td>106.2</td>
<td>121.2</td>
</tr>
</tbody>
</table>

\[ OBJ_{235} = SWL_{r}(\overline{X}) \]  
(36a)

\[ \overline{X} = (p_1, d_1, D_{f1}, DD, xx5, p_2, d_2, xxx1, xxx2, xxx3, xxx4); \]
\[ xx5 = L_s/DDL; \]
\[ DDL = (DD-q_1-q_2-DDf); \]
\[ xxx1 = L_x/Lx; \]
\[ xxx2 = L_y/Ly; \]
\[ xxx3 = L_x/Lx; \]
\[ xxx4 = L_y/Ly; \]  
(36b)

Likewise, the objective function for a three-chamber plenum with a three-layer sound absorber is

\[ OBJ_{235} = SWL_{r}(\overline{X}) \]  
(37a)

\[ \overline{X} = (p_1, d_1, xxx1, DD, xx5, xx6, xx7, p_2, d_2, p_3, d_3, \]
\[ xxx1, xxx2, xxx3, xxx4); \]
\[ xx5 = D_{f1}/DDL; \]
\[ xx6 = D_{f2}/DDf/(1-xx3); \]
\[ xx7 = L_s/DDL/(1-xx5); \]
\[ xxx1 = L_x/Lx; \]
\[ xxx2 = L_y/Ly; \]
\[ xxx3 = L_x/Lx; \]
\[ xxx4 = L_y/Ly; \]  
(37b)

III. CASE STUDIES

As indicated in Fig. 1, to depress a noise from a diesel engine, three kinds of multi-chamber acoustical plenums (one-chamber, two-chamber, and three-chamber) shown in Fig. 2 that are internally lined with four kinds of multi-layer sound absorbers shown in Fig. 3 (one-layer, two-layer, three-layer, and four-layer) are considered. The original sound power level (SWLO) at the diesel engine’s tube outlet is shown in Table 1 where the overall SWLO reaches 121.2 dB(A). A sound absorbing material with a flowing resistant (R) of 4000 (rayls/m) was adopted. To obtain the best acoustical performance within a fixed space, numerical assessments linked to an AIM optimizer were applied. Before the minimization of a broadband noise was executed, a reliability check of the AIM method by maximizing the sound transmission loss of a one-chamber plenum lined with a one-layer sound absorber at a targeted tone (3000 Hz) had been carried out. To achieve the lowest cost in the plenum, the outline dimension of the plenum was 2.0 M in length (Lx), 1.0 M in width (Ly), and 0.8 M in height (Lz). Additionally, the plenum outlet is 0.8M * 0.05 M. Moreover, the total thickness of the perforated plate and the sound absorbing material were fixed at 0.003 M and 0.05 M.

IV. ARTIFICIAL IMMUNE METHOD

The artificial immune method is originated from the organism’s immune system. A book related to the artificial immune method was first published [13]. Also, the papers which were related to the artificial immune method were reorganized [7, 8]. Because the artificial immune method is better in both global and local searching, it has been widely used in various fields to solve optimization problems such as pattern recognition and classification [5], engineering search and optimization methods [12, 23, 26], scheduling [11, 27], data mining [16], and computational security [4, 15].

As indicated in Fig. 4, the antigen appendage cell (APC) will perform the antigen appendage reaction when the antigen (Ag) invades the organism [18]; thereafter, the killer T lymphocyte (T-cell) will recognize the Ag and stimulate the B-cell to select and produce the specific B-cells. When mature, the B-cells will be transformed into a plasma cell and memory cell. Later, the plasma cell will produce antibodies (Ab) to extinguish the Ag. The plasma cells will be transformed into a suppressor T cell when all the antigens are extinguished. Consequently the immune reaction for the organism is terminated. Here, a specific pathogen may be joined distinguished. Consequently, the immune reaction for the organism is terminated. Here, a specific pathogen may be joined distinguished. Consequently, the immune reaction for the organism is terminated. Here, a specific pathogen may be joined distinguished. Consequently, the immune reaction for the organism is terminated. Here, a specific pathogen may be joined distinguished. Consequently, the immune reaction for the organism is terminated. Here, a specific pathogen may be joined.
Ag invasion

initialize Ab (calculation of Ab’s fitness)

choose a better Ab with a specific ratio

clone selection
1. mutation of the light chains
2. fitness calculation
3. renew the memory cell

hypermutation
1. mutation of the heavy chains
2. the exchange of gen segment
3. the replacement between front and back

choose a better Ab with a specific ratio

N ≥ Itermax

Ab randomly generated

program terminated

Fig. 5. Flow diagram of the artificial immune method.

selection and memory and cytokine of Ab, and somatic recombination/somatic mutation/regeneration of Ab’s genes. In the whole immune reaction system, the Ab has the recognition specificity of the Ag. The lymphatic system will produce the appropriate Ab to extinguish the pathogen. When using the immune algorithm in the engineering optimization problem, the problem we solve will be regarded as the Ag, and the solution will be Ab. Based on the targeted Ag, the best Ag will be searched for step by step. During the immune optimization, the best gene Ab will be selected and put into the memory cell for individual generation. Thereafter, the best genes will be kept and used in the next evolution after the screening process in the memory cell. Each Ab coded by binary bits presents one solution. The string length of the Ab is composed of design parameters. The flow diagram of the artificial immune method is shown in Fig. 5. In the artificial immune optimization, the operation will be repeated until the integrated iteration reaches a maximal iteration preset in the program.

AbAg = OBJ (X) (40)

where Ab is the anti-body, xN is the N-th design parameter, Ag is the anti-gene, and AbAg is the affinity between the Ab and Ag. The relationship mentioned above is shown in Fig. 6.

V. RESULTS AND DISCUSSION

The accuracy of the AIM optimization depends on the abn (antibody number), the cn (clone number), the maxGen (max iteration), the mf (mutation Factor), the rmtr (remove threshold), the cstr (clonal selection threshold), and the div (diversity). To investigate the influences of the above AIM’s control parameters, assessed ranges of the AIM parameters are

abn = (10, 30, 50); cn = (5, 10, 20); maxGen = (10, 20, 30);
mf = (30, 50, 80); rmtr = (0.05, 0.1, 0.2);
cstr = (0.005, 0.01, 0.02); div = (0.1, 0.3, 0.5).

The results of two optimizations — one, a pure tone noise used for the AIM’s accuracy check; and the other, a broadband noise occurring in an air compressor — are described below.

1. Results

1) Pure Tone Noise Optimization

By using Eq. (28), the maximization of the sound transmission loss with respect to a one-chamber plenum lined with a one-layer sound absorber (R = 4000 rayls/m) at the specified pure tone (3000 Hz) was performed first. As indicated in Table 2, fifteen sets of AIM parameters were tried in the acoustical plenum’s optimization. Obviously, the optimal design data can be obtained from the last set of AIM parameters at (abn, cn, maxGen, mf, rmtr, cstr, div). Table 2 reveals that the optimal design data was obtained at the last set of AIM parameters at (30, 30, 30, 0.05, 0.02, 0.1). Using the optimal
Table 2. Optimal results of a one-chamber plenum lined with a one-layer sound absorber with respect to various AIM parameters at targeted tones of 3000 Hz.

<table>
<thead>
<tr>
<th>Item</th>
<th>abn</th>
<th>cn</th>
<th>maxGen</th>
<th>mf</th>
<th>rmtr</th>
<th>cstr</th>
<th>div</th>
<th>p%</th>
<th>d</th>
<th>DD</th>
<th>STL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>5</td>
<td>20</td>
<td>30</td>
<td>0.2</td>
<td>0.01</td>
<td>0.5</td>
<td>26.5</td>
<td>0.012</td>
<td>0.099</td>
<td>20.9</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>5</td>
<td>20</td>
<td>30</td>
<td>0.2</td>
<td>0.01</td>
<td>0.5</td>
<td>37.0</td>
<td>0.008</td>
<td>0.098</td>
<td>22.2</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>5</td>
<td>20</td>
<td>30</td>
<td>0.2</td>
<td>0.01</td>
<td>0.5</td>
<td>31.2</td>
<td>0.004</td>
<td>0.092</td>
<td>22.3</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>0.2</td>
<td>0.01</td>
<td>0.5</td>
<td>14.9</td>
<td>0.008</td>
<td>0.057</td>
<td>23.3</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>0.2</td>
<td>0.01</td>
<td>0.5</td>
<td>7.5</td>
<td>0.015</td>
<td>0.056</td>
<td>23.4</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>20</td>
<td>10</td>
<td>30</td>
<td>0.2</td>
<td>0.01</td>
<td>0.5</td>
<td>38.9</td>
<td>0.003</td>
<td>0.097</td>
<td>23.9</td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>20</td>
<td>30</td>
<td>30</td>
<td>0.2</td>
<td>0.01</td>
<td>0.5</td>
<td>32.8</td>
<td>0.012</td>
<td>0.053</td>
<td>28.7</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>20</td>
<td>30</td>
<td>80</td>
<td>0.2</td>
<td>0.01</td>
<td>0.5</td>
<td>15.4</td>
<td>0.013</td>
<td>0.054</td>
<td>28.7</td>
</tr>
<tr>
<td>9</td>
<td>50</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>0.2</td>
<td>0.01</td>
<td>0.5</td>
<td>30.1</td>
<td>0.009</td>
<td>0.054</td>
<td>29.2</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>0.1</td>
<td>0.01</td>
<td>0.5</td>
<td>14.5</td>
<td>0.005</td>
<td>0.054</td>
<td>29.2</td>
</tr>
<tr>
<td>11</td>
<td>50</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>0.05</td>
<td>0.01</td>
<td>0.5</td>
<td>12.9</td>
<td>0.014</td>
<td>0.053</td>
<td>29.2</td>
</tr>
<tr>
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<td>30</td>
<td>50</td>
<td>0.05</td>
<td>0.005</td>
<td>0.5</td>
<td>39.3</td>
<td>0.007</td>
<td>0.054</td>
<td>29.3</td>
</tr>
<tr>
<td>13</td>
<td>50</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>0.05</td>
<td>0.02</td>
<td>0.5</td>
<td>24.2</td>
<td>0.009</td>
<td>0.054</td>
<td>29.3</td>
</tr>
<tr>
<td>14</td>
<td>50</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>0.05</td>
<td>0.02</td>
<td>0.3</td>
<td>28.5</td>
<td>0.013</td>
<td>0.054</td>
<td>29.3</td>
</tr>
<tr>
<td>15</td>
<td>50</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>0.05</td>
<td>0.02</td>
<td>0.1</td>
<td>15.5</td>
<td>0.009</td>
<td>0.054</td>
<td>29.3</td>
</tr>
</tbody>
</table>

Fig. 7. STLs with respect to frequencies at various AIM parameters (abn, cn) [a one-chamber plenum lined with a one-layer sound absorber] (targeted tone: 3000 Hz).

Fig. 8. STLs with respect to frequencies at various AIM parameters (maxGen, mf, rmtr) [a one-chamber plenum lined with a one-layer sound absorber] (targeted tone: 3000 Hz).

Fig. 9. STLs with respect to frequencies at various AIM parameters (cstr, iter) [a one-chamber plenum lined with a one-layer sound absorber] (targeted tone: 3000 Hz).

design data in a theoretical calculation, the resulting curves of the STL with respect to various AIM parameters (abn, cn, maxGen, mf, rmtr, cstr, div) are depicted in Figs. 7–9. As revealed in Fig. 9, the STL is precisely maximized at the desired frequency.

2) Broadband Noise Optimization

To realize the influence of the silenced overall sound power level (SWL_T) with respect to three kinds of multi-chamber plenums (one-chamber, two-chamber, and three-chamber) equipped with three kinds of sound absorbers (one-layer, two-layer, three-layer, four-layer) at the wool’s flow resistance (R) of 4000 (rayls/m), formulas of Eqs. (29)-(37) in conjunction with the AIM optimizer using the AIM parameters of (abn = 50, cn = 20, maxGen = 30, mf = 50, rmtr = 0.05, cstr = 0.02, div = 0.1) were performed. The optimal SWL_T of a one-chamber plenum with respect to three kinds of sound absorbers is obtained in Table 3. Similarly, the optimal SWL_T of a two-chamber plenum with respect to three kinds of sound absorbers is obtained in Table 4. Likewise, the optimal resulting SWL_T of a three-chamber plenum with respect to three kinds of sound absorbers is shown in Table 5. Using the optimal design data in a theoretical calculation for three kinds of multi-chamber plenums, the resulting curves of the SWL_T with respect to three kinds of sound absorbers in conjunction
Table 3. Optimal results for a one-chamber plenum equipped with three kinds of multi-layer sound absorbers (broadband noise).

<table>
<thead>
<tr>
<th>Item</th>
<th>Design parameters</th>
<th>$\text{SWL}_T$ – dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) A plenum equipped with a one-layer sound absorber</td>
<td>$p%$ $d\text{(m)}$ $DD\text{(m)}$ $xx4$ $p_2%$</td>
<td>87.9</td>
</tr>
<tr>
<td></td>
<td>39.3 0.0080 0.102</td>
<td></td>
</tr>
<tr>
<td>(B) A plenum equipped with a two-layer sound absorber</td>
<td>$p_1%$ $d_1\text{(m)}$ $D_{11}\text{(m)}$ $DD\text{(m)}$ $xx5$ $xx6$</td>
<td>79.0</td>
</tr>
<tr>
<td></td>
<td>23.4 0.007 0.010 0.066 0.088 36.2</td>
<td></td>
</tr>
<tr>
<td>(C) A plenum equipped with a three-layer sound absorber</td>
<td>$p_1%$ $d_1\text{(m)}$ $xx7$ $DD\text{(m)}$ $xx5$ $xx6$</td>
<td>88.2</td>
</tr>
<tr>
<td></td>
<td>31.9 0.014 0.224 0.103 0.960 0.015</td>
<td></td>
</tr>
</tbody>
</table>

Note: $xx3 = D_{ll}/DDf$; $xx4 = L_s/DDL$; $xx5 = D_{ll}/DDf(1-D_{ll}/DDf)$; $xx6 = D_{ll}/DDf(1-D_{ll}/DDf)$; $xx7 = L_s/DDL(1-L_s/DDL)$; $xx8 = D_{ll}/DDf(1-D_{ll}/DDf)/\text{(1-xx6)}$; $xx9 = L_s/DDL(1-L_s/DDL)/\text{(1-xx7)}$; $DDL = (DD-q1-q2-DDf)$

Table 4. Optimal results for a two-chamber plenum equipped with three kinds of multi-layer sound absorbers (broadband noise).

<table>
<thead>
<tr>
<th>Item</th>
<th>Design parameters</th>
<th>$\text{SWL}_T$ – dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) A plenum equipped with a one-layer sound absorber</td>
<td>$p%$ $d\text{(m)}$ $DD\text{(m)}$ $xx1$ $xx2$</td>
<td>72.0</td>
</tr>
<tr>
<td></td>
<td>39.7 0.006 0.055 0.221 0.876</td>
<td></td>
</tr>
<tr>
<td>(B) A plenum equipped with a two-layer sound absorber</td>
<td>$p_1%$ $d_1\text{(m)}$ $D_{11}\text{(m)}$ $DD\text{(m)}$ $xx4$ $p_2%$</td>
<td>56.3</td>
</tr>
<tr>
<td></td>
<td>29.9 0.009 0.013 0.094 0.261 35.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.008 0.314 0.826</td>
<td></td>
</tr>
<tr>
<td>(C) A plenum equipped with a three-layer sound absorber</td>
<td>$p_1%$ $d_1\text{(m)}$ $xx3$ $DD\text{(m)}$ $xx5$ $xx6$</td>
<td>64.3</td>
</tr>
<tr>
<td></td>
<td>21.8 0.003 0.449 0.083 0.339 0.186</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.344 29.3 0.003 25.2 0.008 0.261</td>
<td></td>
</tr>
</tbody>
</table>

Note: $xx3 = D_{ll}/DDf$; $xx4 = L_s/DDL$; $xx5 = D_{ll}/DDf(1-D_{ll}/DDf)$; $xx6 = D_{ll}/DDf(1-D_{ll}/DDf)$; $xx7 = L_s/DDL(1-L_s/DDL)$; $xx8 = D_{ll}/DDf(1-D_{ll}/DDf)/\text{(1-xx6)}$; $xx9 = L_s/DDL(1-L_s/DDL)/\text{(1-xx7)}$; $DDL = (DD-q1-q2-DDf)$; $xx1 = L_x/L_s$

with the original SWL are plotted in Figs. 10–12. Similarly, for a specified layer of sound absorber, the resulting curves of the SWL$_T$ with respect to three kinds of chambers in conjunction with the original SWL are plotted in Figs. 13–15. As illustrated in Table 3, the overall sound power levels of a one-chamber plenum with respect to three kinds of sound absorbers will be improved from 121.2 dB(A) to 87.9 dB(A), 79.0 dB(A), and 88.2 dB(A), respectively. Similarly, as illustrated in Table 4, the overall sound power levels of a two-chamber plenum with respect to three kinds of sound absorbers will be improved from 121.2 dB(A) to 72.0 dB(A), 56.3 dB(A), and 64.3 dB(A), respectively. Equally, as illustrated in Table 5, the overall sound power levels of a three-chamber plenum with respect to three kinds of sound absorbers will be improved from 121.2 dB(A) to 75.1 dB(A), 79.7 dB(A), and 60.1 dB(A), respectively.

2. Discussion

To achieve sufficient optimization, the selection of the appropriate AIM parameter set is essential. As indicated in Table 2 and Figs. 7–9, the predicted maximal value of the sound transmission loss STL for the best AIM set of a one-chamber plenum lined with a one-layer sound absorber is precisely located at the desired frequency of 3000 Hz. Therefore, the use of the AIM optimization in finding a better design solution is reliable; moreover, three kinds of multi-chamber plenums (one-chamber, two-chamber, and three-chamber) lined with three kinds of sound absorbers (one-layer, two-layer, and three-layer) shown in Fig. 2(A), (B), and (C) are adopted to eliminate the broadband noise.
As indicated in Table 3, the overall sound transmission loss of the optimally shaped one-chamber acoustical plenum with respect to three kinds of sound absorbers reaches 33.3 dB(A), 42.2 dB(A), and 33.0 dB(A). Similarly, as indicated in Table 4, the overall sound transmission loss of the optimally shaped two-chamber acoustical plenum with respect to three kinds of sound absorbers reaches 49.2 dB(A), 64.9 dB(A), and 56.9 dB(A). Equally, as indicated in Table 5, the overall sound transmission loss of the optimally shaped three-chamber acoustical plenum with respect to three kinds of sound absorbers reaches 33.3 dB(A), 46.1 dB(A), and 61.1 dB(A). As indicated in Tables 3–5 and Figs. 10–12, the overall sound transmission loss of the plenum will possibly increase if the number of the layer increases. As can be seen in Figs. 13–15, when using sound absorbers with single layer, the overall

![Fig. 10. STLs of one-chamber plenums lined with three kinds of multi-layer sound absorbers (one-layer, two-layer, and three-layer) [wool’s flowing resistance = 4000 rayls/m] [broadband noise].](image1)

![Fig. 11. STLs of two-chamber plenums lined with three kinds of multi-layer sound absorbers (one-layer, two-layer, and three-layer) [wool’s flowing resistance = 4000 rayls/m] [broadband noise].](image2)

![Fig. 12. STLs of three-chamber plenums lined with three kinds of multi-layer sound absorbers (one-layer, two-layer, and three-layer) [wool’s flowing resistance = 4000 rayls/m] [broadband noise].](image3)
sound transmission loss of the plenum will increase if the number of the plenum’s chamber increases.

VI. CONCLUSION

It has been shown that the multi-chamber acoustical plenum lined with multi-layer sound absorber in conjunction with an AIM optimizer can be efficiently optimized within a constrained space. As indicated in Table 2, seven kinds of AIM parameters (abn, cn, maxGen, mf, rmtr, cstr, and div) play essential roles in the solution’s accuracy during the AIM optimization. As indicated in Fig. 9, the sound transmission loss is precisely maximized at the desired frequency; therefore, the tuning ability established by adjusting the design parameters of the acoustical plenum is reliable. In addition, the appropriate acoustical performance curve of the acoustical plenum in decreasing the overall broadband noise using three chambers (one-chamber, two-chamber, and three-chamber) as well as three sound absorbers (one-layer, two-layer, and three-layer) has been assessed and shown in Tables 3–5 and Figs. 10–15. As indicated in Figs. 13–15, when using sound absorbers with single layer, the acoustical performance of an acoustical plenum will increase if the number of chamber increases.

Consequently, this approach used for optimally designing the shaped multi-chamber acoustical plenum lined with multi-layer sound absorbers within a constrained space is economical and quite effective.

NOMENCLATURE

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

- Ab the antibody
- Abn the antibody number
- Ag the antigen
- APC the antigen appendage cell
- cn the clone number
- cstr the clonal selection threshold
- \( C_0 \) sound speed (m s\(^{-1}\))
- \( d_i \) diameter of perforated hole on the front plate (m)
- \( d_{dk} \) the diameter from inlet to outlet of the \( k \)-th chamber plenum
- \( DD \) the total thickness of the acoustic panel
- \( D_{TF} \) the total thickness of the acoustic fiber
- \( D_{i0} \) the thickness of the \( i \)-layer acoustic fiber
- div the diversity
- \( Ig \) the immunoglobulins
- \( j \) imaginary unit
- \( k \) wave number (\( = \omega c_0 \))
- \( k_{\text{Re}} \) real part of complex \( k_{\text{fiber-}i} \)
- \( k_{\text{Im}} \) image part of complex \( k_{\text{fiber-}i} \)
- \( k_{\text{fiber-}i} \) complex propagation constant of the \( i \)-th layer of the acoustic fiber
- \( L_i \) air depth of the \( i \)-th layer of the sound absorber (m)
$L_{x}, L_{y}, L_{z}$  the outline dimension of the plenum (m)
$L_{xi}$  the horizontal distance of the $i$-th baffle within the plenum (m)
$L_{yi}$  the vertical depth of the $i$-th baffle within the plenum (m)
$maxGen$  the maximum iteration
$mf$  the mutation factor
$N$  hole’s number on the perforated front plate per 1 m$^2$
$OBJ$  objective function
$\rho_{i}$  porosity of the perforated plate ($= \varepsilon * 100\%$) (%)
$\rho_{oc}$  air density (kg m$^{-3}$)
$\rho_{c}$  the acoustic impedance
$p_{iT}$  acoustic pressure at $i$ (Pa)
$q_{i}$  thickness of the $i$-th layer of the perforated plate (m)
$q_{iT}$  the total thickness of the perforated front plate
$R_{i}$  acoustic flow resistance of the $i$-th layer of the acoustic fiber (MKS rayls m$^{-1}$)
$R_{f}$  acoustic flow resistivity of the acoustic fiber (MKS rayls m$^{-2}$)
$R_{f-i}$  real part of the $i$-th layer of complex $Z_{fiber}$
$rmtr$  the remove threshold
$S_{c}$  the area of the plenum outlet
$STL$  the sound transmission loss of an acoustical plenum
$S_{w}$  the total area of the plenum wall
$SWL_{f}$  the silenced sound power level after adding an acoustical plenum
$SWLO$  the unsilenced sound power level within the compressor outlet
$u_{i}$  acoustic particle velocity at $i$ (kg s$^{-1}$)
$W_{IN-i}$  the input acoustic power at the inlet of the $i$-th chamber plenum (joule s$^{-1}$)
$W_{df-i}$  the acoustic power in the direct field at the outlet of the $i$-th chamber plenum (joule s$^{-1}$)
$W_{OUT-i}$  the output acoustic power at the outlet of the $i$-th chamber plenum (joule s$^{-1}$)
$W_{rf-i}$  the acoustic power in the reverberant field at the outlet of the $i$-th chamber plenum (joule s$^{-1}$)
$Z_{i}$  specific normal impedance at $i$
$Z_{f-i}$  characteristic impedance of the $i$-th layer of the acoustic fiber
$Z_{pi}$  characteristic impedance of the $i$-th perforated front plate
$X_{fiber-i}$  image part of the $i$-th layer of complex $Z_{fiber}$
$\alpha_{i}$  sound absorption coefficient of the $i$-th layer sound absorber
$\alpha_{i}$  average sound absorption coefficient within a plenum using the $i$-layer sound absorber
$\omega$  angular frequency (rad s$^{-1}$)
$\delta_{j}$  the angle between the diagonal line for the $k$-th chamber plenum (rad s$^{-1}$)
$\nu$  kinematic viscosity of air ($= 15*10^{-6}$ m$^2$/s)
$\varepsilon_{i}$  porosity of the $i$-th layer of the perforated plate (m)
$\delta_{i}$  viscous boundary layer thickness of the $i$-th layer of the perforated plate (m)

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REFERENCES


