3. Noise control for a reverberant sound field within an enclosed machine room

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Abstract. Because of the strong reverberant effect within an enclosed machine room, the noise control using sound absorber and acoustical hood is essential. In previous experience, the traditional method for designing a sound absorber and an acoustical enclosure has proven to be time-consuming. In order to efficiently control the noise level, an interest in the shape optimization of a sound absorber as well as acoustical enclosure is necessary. In this paper, the theoretical sound propagation model and the method of minimized variation square is proposed and linked with a particle swarm optimization (PSO). Three kinds of multi-equipment machine rooms using the sound absorber and an acoustical enclosure in conjunction with the PSO method has been introduced. Before noise abatement is carried out, the accuracy of the mathematical model in a single-noise enclosed system will be checked by SoundPlan (a professional simulation package). Results reveal that both the acoustical panel and the acoustical enclosure can be efficiently designed. Consequently, this paper may provide an efficient way in depressing both the direct and reflected sound wave.

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1. Introduction

Lan and Chiu [1] reduced the noise level by adjusting the location of noisy equipment. In order to economically control the noise level specified by the Environmental Protection Agency, Chiu [2] depressed the noise propagation by optimally adjusting equipment allocation and searching for a shaped sound barrier around the plant’s boundary. Roberts and Murray [3] proposed a muffler system used to eliminate direct sound wave emitted from a venting device. Sanders [4] also developed a composite sound barrier panel used to eliminate a direct sound effect emitted from a piece of equipment. Nevertheless, there are two primary sound energies (direct sound and reverberant sound) within a space-constrained machine room. Neither the allocation adjustment nor the shaped sound barrier is useful in depressing a reverberant sound propagating within an enclosed building. To efficiently reduce the hybrid noise within a machine room, an optimal exploration using a one-layer acoustical panel as well as an acoustical enclosure is obligatory. Moreover, in order to ease the optimization procedure, particle swarm optimization (PSO), one of the modern heuristic algorithms deduced by Kennedy and Eberhart [5, 6, 7] is used.

2. Theoretical background

2.1. Sound absorption coefficient

As studied in previous paper [8, 9], for a plane wave propagating perpendicularly through a partitioned and uniform section filled with a quiescent medium (symbolized by “m”), the general matrix form between point 1 and point 2 is expressed as

\[
\begin{pmatrix}
    p_2 \\
    u_2
\end{pmatrix} =
\begin{bmatrix}
    \cos(k_m L) & jZ_m \sin(k_m L) \\
    jL_m \sin(k_m L) & \cos(k_m L)
\end{bmatrix}
\begin{pmatrix}
    p_1 \\
    u_1
\end{pmatrix}
\]

(1)

For a one-layer perforated absorber shown in Fig. 1(C), the structure of a partitioned one-layer sound absorber includes (1) \(L\) thickness of the air space; (2) \(D_f\) thickness of the absorbing wool layer; (3) \(q\) thickness of the perforated front plate (with \(m\) at the surface density of the perforated front plate, \(d_H\) the diameter of the perforated hole on the front plate, and \(p\%\) the perforated ratio of the perforated front plate). By using Eq.(1), the transfer matrix of acoustic pressure \(p\) and acoustic particle velocity \(u\) between points 0 and 1 is
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Figure 1. The plan view and section view for a multi-equipment machine room equipped with an acoustical panel and an acoustical enclosure.

\[
\begin{bmatrix}
  p_1 \\
  u_1
\end{bmatrix} =
\begin{bmatrix}
  \cos(\omega L / c_o) & j\rho_o c \sin(\omega L / c_o) \\
  j & \rho_o c_o
\end{bmatrix}
\begin{bmatrix}
  p_o \\
  u_o
\end{bmatrix}
\]  

(2)

where \( p_1 \) is the sound pressure at the surface of the air layer, \( u_1 \) is the acoustic particle velocity at the surface of the air layer, \( p_o \) is the acoustic pressure at the wall, and \( u_o \) is the acoustic particle velocity at the wall. The normal impedance \( Z_{\text{air}} \) at the air layer is simplified as

\[
Z_1 = Z_{\text{air}} = -j\rho_o c_o \cot(\omega L / c_o)
\]  

(3)

The transfer matrix of the acoustic pressure \( p \) and the acoustic particle velocity \( u \) between points 1 and 2 yields
\[
\begin{bmatrix}
 p_2 \\
 u_2
\end{bmatrix} =
\begin{bmatrix}
 \cos[K_{\text{fiber}}(Df)] & jZ_{\text{fiber}} \sin[K_{\text{fiber}}(Df)] \\
 j \frac{Z_{\text{fiber}}}{Z_{\text{fiber}}(Df)} & \cos[K_{\text{fiber}}(Df)]
\end{bmatrix}
\begin{bmatrix}
 p_1 \\
 u_1
\end{bmatrix}
\] (4)

Plugging Eq. (3) into Eq. (4), the normal impedance \( Z_2 \) at the surface of the wool layer is

\[
Z_2 = \frac{Z_1 \cos[K_{\text{fiber}}(Df)] + j(R_{\text{fiber}} + jX_{\text{fiber}}) \sin[K_{\text{fiber}}(Df)]}{jZ_1 \sin[K_{\text{fiber}}(Df)] + \cos[K_{\text{fiber}}(Df)]}
\] (5)

Adopting the formula of the characteristic impedance and the wave number, derived by Delany & Bazley [10] yields

\[
K_{1,2} = \left\{ \frac{\omega(Df)}{c_o} \right\} \left[ 1 + 0.0978\left( \frac{\rho_o f}{R_f} \right)^{-0.700} \right] ;
\]

\[
K_{2,2} = \left\{ \frac{\omega(Df)}{c_o} \right\} \left[ -0.189\left( \frac{\rho_o f}{R_f} \right)^{-0.595} \right] ;
\]

\[
R_{\text{fiber}} = \rho_o c_o (1 + 0.0571\left( \frac{\rho_o f}{R_f} \right)^{-0.754}) ;
\]

\[
X_{\text{fiber}} = \rho_o c_o (-0.087\left( \frac{\rho_o f}{R_f} \right)^{-0.732})
\] (6a, 6b, 6c)

where \( K_{\text{fiber}} = K_{1,2} + jK_{2,2} ; 1000 \leq R_f \leq 50000 \)

The transfer matrix of the acoustic pressure \( p \) and the acoustic particle velocity \( u \) between points 2 and 3 has

\[
\begin{bmatrix}
 p_3 \\
 u_3
\end{bmatrix} =
\begin{bmatrix}
 \cos(K_p q) & jZ_p \sin(K_p q) \\
 j \frac{Z_p}{Z_p(Df)} & \cos(K_p q)
\end{bmatrix}
\begin{bmatrix}
 p_2 \\
 u_2
\end{bmatrix}
\] (7)

By developing Eq. (7) and adopting the specific normal impedance and the wave number of the perforated plate deduced by Ingard & Bolt [11] yield

\[
Z_3 = \frac{Z_p Z_2 + jZ_p \tan(K_p q)}{Z_p + jZ_2 \tan(K_p q)}
\] (8a)
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where

\[
Z_p = j32\pi M_h \left\{ \left[ 1 + \frac{16M_h}{mN\pi^2 dH^4} \right] \right\};
\]

\[
M_h = \rho_o \left\{ \frac{\pi dH^2 q}{4} + \frac{2dH^3}{3} \right\}
\]

For an incident sound wave normally propagating into an acoustical panel, the normal sound absorption coefficient \((\alpha_k)\) at \(k\) frequency is

\[
\alpha_k(D_f, L_d, f_k, q, dH, m, p\%) = 1 - \frac{Z_3 - \rho_o c_o}{Z_3 + \rho_o c_o}^2
\]

### 2.2. Acoustical calculation within a machine room [9]

For an enclosed machine room (LL in width, WW in length, and HH in height) shown in Fig. 1, the sound pressure level \((SPL_{ijk})\) of a specific sound receiver \((j)\) emitted from a specific machine \((i)\) that is equipped with an acoustical enclosure \((IL_{ik})\) at \(k\) frequency is

\[
SPL_{ijk} = SWL(f_{ik}, x_i, y_i, z_i, r_{ij}, \phi_{ij}, zr_{ij}, \alpha_k, LL, WW, HH)
\]

\[
= SWL(f_{ik}) - IL_{ik} - \Psi_{ik}(r_{ij}, \phi, f_k) + 10\log \left( \frac{Q_i}{4\pi r_{ij}^2} + \frac{4}{RR_k} \right)
\]

\[
RR_k = \sum_{i=1}^{n} \frac{SS_i\alpha_{ik}}{1 - \sigma_i}; \Psi_{ik}(r_{ij}, \phi, f_k) = 7.4 \left( \frac{r_{ij} f_k^2}{\phi} \right) \cdot 10^{-3} \cdot \frac{SS_i\alpha_{ik}}{\sum_{i=1}^{n} SS_i}
\]

where \(IL_{ik}\) is the sound insertion loss of the \(i\)-th equipment at the \(k\)-th octave band, \(\Psi_{ik}(r_{ij}, \phi, f_k)\) is the air’s sound absorption at \(20^\circ C\), \(f_k\) is the sound frequency and \(\phi\) is the humidity in air.

By integrating the sound from all equipment \((n)\), the sound pressure level \((SPL_{jk})\) of a specific sound receiver \((j)\) at \(k\) frequency is

\[
SPL_{jk} = 10 \times \log \left( \sum_{i=1}^{n} 10^{\frac{SPL_{ijk}}{10}} \right)
\]
For a j-th sound receiver \((j)\), the overall SPL is calculated by summing the SPL of the individual octave band \(k\) \((k=1\) to \(m)\).

\[
SPL_j = 10 \times \log \left\{ \sum_{k=1}^{m} 10^{\frac{SPL_{j,k}}{10}} \right\}
\]  

(12)

2.3. Objective function [9]

Based on the targeted \(SPL_{\text{target}}\) within a room, the objective function in minimizing the variation of \(SPL\) with respect to the targeted \(SPL_{\text{target}}\) at the receiving points \((nn)\) is

\[
OBJ(\text{IL}_{\text{a,k}}, D_f, R_f, dH, p\%) = \sum_{j=1}^{nn} (SPL_{\text{target}} - SPL_j)^2
\]

(13)

Three cases of various equipment allocations inside the machine room are described below.

Case I: One equipment inside a machine room

The allocation of a single piece of equipment inside a machine room is shown in Fig.2. Based on section 2.2, the related objective function and the ranges of the parameters are
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\[
\begin{align*}
OB_J &\left(p\% , dH , D_J , R_J , IL_{1,125Hz} , IL_{1,250Hz} , IL_{1,500Hz} , IL_{1,1000Hz} , IL_{1,2000Hz}\right) \\
&= OB_J(\sum_{j=1}^{5} (SPI_{\text{target}} - SPL_j))
\end{align*}
\]  

(14a)

\[
RT_1 (= p\% ) : [5, 23]; \ RT_2 (= dH ) : [0.003, 0.015]; \ RT_3 (= D_J ) : [0, 0.09]; \\
RT_4 (= R_J ) : [3000, 20000]; \ RT_5 (= IL_{1,125Hz} ) : [0, 10]; \\
RT_6 (= IL_{1,250Hz} ) : [0, 15]; \ RT_7 (= IL_{1,500Hz} ) : [0, 20]; \\
RT_8 (= IL_{1,1000Hz} ) : [0, 25]; \ RT_9 (= IL_{1,2000Hz} ) : [0, 25];
\]  

(14b)

**Case II: Two equipment inside a machine room**

Similarly, the allocation of a two pieces of equipment inside a machine room is shown in Fig.3. The related objective function and the ranges of the parameters are

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**Figure 3.** The plan view and section view for a machine room with two pieces of equipment (CASE II).
\[ OBJ_2(p\%_dH, D_f, R_f, I_{L_{1250Hz}}, I_{L_{2500Hz}}, I_{L_{1000Hz}}, I_{L_{1250Hz}}, I_{L_{2500Hz}}, I_{L_{1000Hz}}, I_{L_{1250Hz}}) = OBJ_2(RT_1^*, RT_2^*, RT_3^*, RT_4^*, RT_5^*, RT_6^*, RT_7^*, RT_8^*, RT_9^*, RT_{10}^*, RT_{11}^*, RT_{12}^*, RT_{13}^*, RT_{14}^*) \]
\[ = \sum_{j=1}^{2} (SPL_{target} - SPL_j)^2 \]

Case III: Three equipment inside a machine room

Likewise, the allocation of a three pieces of equipment inside a machine room is shown in Fig. 4. The related objective function and the ranges of parameters are

\[ OBJ_1(p\%_dH, D_f, R_f, I_{L_{1250Hz}}, I_{L_{2500Hz}}, I_{L_{5000Hz}}, I_{L_{1000Hz}}, I_{L_{1250Hz}}) = OBJ_1(RT_{1}^{**}, RT_{2}^{**}, RT_{3}^{**}, RT_{4}^{**}, RT_{5}^{**}, RT_{6}^{**}, RT_{7}^{**}, RT_{8}^{**}, RT_{9}^{**}, RT_{10}^{**}, RT_{11}^{**}, RT_{12}^{**}, RT_{13}^{**}, RT_{14}^{**}) \]
\[ = \sum_{j=1}^{2} (SPL_{target} - SPL_j)^2 \]

\[ RT_1^{**} (= p\%) : [5, 23]; RT_2^{**} (= dH) : [0.003, 0.015]; RT_3^{**} (= D_f) : [0, 0.09]; \]

\[ RT_4^{**} (= R_f) : [3000, 20000]; RT_5^{**} (= I_{L_{1250Hz}}) : [0, 10]; \]

\[ RT_6^{**} (= I_{L_{2500Hz}}) : [0, 15]; RT_7^{**} (= I_{L_{5000Hz}}) : [0, 20]; \]

\[ RT_8^{**} (= I_{L_{1000Hz}}) : [0, 25]; RT_9^{**} (= I_{L_{2000Hz}}) : [0, 25]; \]

\[ RT_{10}^{**} (= I_{L_{2500Hz}}) : [0, 15]; RT_{11}^{**} (= I_{L_{2000Hz}}) : [0, 25]; \]

\[ RT_{12}^{**} (= I_{L_{5000Hz}}) : [0, 25]; RT_{13}^{**} (= I_{L_{1500Hz}}) : [0, 25]; \]

\[ RT_{14}^{**} (= I_{L_{2000Hz}}) : [0, 25]; \]

\[ RT_1^{**} = RT_2^{**} = RT_3^{**} = RT_4^{**} = RT_5^{**} = RT_6^{**} = RT_7^{**} = RT_8^{**} = RT_9^{**} = RT_{10}^{**} = RT_{11}^{**} = RT_{12}^{**} = RT_{13}^{**} = RT_{14}^{**} \]
\[ RT_4^{**} (= R_T) : [3000, 20000]; \] \[ RT_5^{**} (= IL_{1,125\text{Hz}}) : [0, 10]; \] \[ RT_6^{**} (= IL_{1,250\text{Hz}}) : [0, 15]; \] \[ RT_7^{**} (= IL_{1,500\text{Hz}}) : [0, 20]; \] \[ RT_8^{**} (= IL_{1,1000\text{Hz}}) : [0, 25]; \] \[ RT_9^{**} (= IL_{1,2000\text{Hz}}) : [0, 25]; \] \[ RT_{10}^{**} (= IL_{2,125\text{Hz}}) : [0, 10]; \] \[ RT_{11}^{**} (= IL_{2,250\text{Hz}}) : [0, 15]; \] \[ RT_{12}^{**} (= IL_{2,500\text{Hz}}) : [0, 20]; \] \[ RT_{13}^{**} (= IL_{2,1000\text{Hz}}) : [0, 25]; \] \[ RT_{14}^{**} (= IL_{2,2000\text{Hz}}) : [0, 25]; \] \[ RT_{15}^{**} (= IL_{3,125\text{Hz}}) : [0, 10]; \] \[ RT_{16}^{**} (= IL_{3,250\text{Hz}}) : [0, 15]; \] \[ RT_{17}^{**} (= IL_{3,500\text{Hz}}) : [0, 20]; \] \[ RT_{18}^{**} (= IL_{3,1000\text{Hz}}) : [0, 25]; \] \[ RT_{19}^{**} (= IL_{3,2000\text{Hz}}) : [0, 25]; \] (16b)

**Figure 4.** The plan view and section view for a machine room with three pieces of equipment (CASE III).

### 3. Model Check [9]

To verify the reliability of the mathematical model of the sound attenuation equation in Eqs.(10-12), an accuracy check is performed by
using the simulated data from SoundPlan [13]. Therefore, a single-noise inside a fully enclosed building (60, 40 and 8 meters in $X$, $Y$ and $Z$ axes) shown in Fig. 5 is introduced and assessed. The equipment with a $SWL$ of 120 dB(A) at 1000Hz is allocated at (20, 15, 2). Additionally, the related sound absorption coefficients of the internal walls, ceiling, and ground are listed in Table 1.

**Figure 5.** Allocation plan of a building with a single piece of equipment inside.

**Table 1.** Sound absorption coefficients of the enclosed building.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound Absorption Coefficient (walls+ceiling)</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>0.92</td>
<td>0.93</td>
<td>0.85</td>
<td>0.8</td>
</tr>
<tr>
<td>Sound Absorption Coefficient (ground)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

To verify the reliability of the aforementioned mathematical model, the 77-point monitoring system is applied, concomitantly. By plugging the $SWL$ and the coordinates into Eqs. (10-12) and SoundPlan, the relevant $SPL$ at the receiving points are calculated and shown in Table 2. The internal noise contour map simulated by SoundPlan, a professional sound calculation package, is depicted in Fig. 6. As indicated in Table 2, the variations of $SPL$
between the mathematical model and SoundPlan are between –1.9~+1.9 dB(A), a small difference; therefore, the accuracy of this mathematical model is acceptable.

Table 2. Accuracy check for the theoretical model and SoundPlan at sixty-six receiving points [unit: in dB(A)] [16].

<table>
<thead>
<tr>
<th>Monitoring point</th>
<th>PT1</th>
<th>PT2</th>
<th>PT3</th>
<th>PT4</th>
<th>PT5</th>
<th>PT6</th>
<th>PT7</th>
<th>PT8</th>
<th>PT9</th>
<th>PT10</th>
<th>PT11</th>
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</thead>
<tbody>
<tr>
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<td>87.9</td>
<td>88.5</td>
<td>88.8</td>
<td>88.5</td>
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<td>87.3</td>
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<td>89.1</td>
<td>90.4</td>
<td>91.1</td>
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<td>SoundPlan</td>
<td>89.7</td>
<td>89.8</td>
<td>90.1</td>
<td>89.8</td>
<td>89.0</td>
<td>88.0</td>
<td>87.0</td>
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<td>92.2</td>
<td>93.0</td>
<td>92.0</td>
</tr>
<tr>
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<td>-1.3</td>
<td>-1.3</td>
<td>-1.1</td>
<td>-0.7</td>
<td>-0.2</td>
<td>-1.7</td>
<td>-1.8</td>
<td>-1.9</td>
<td>-1.6</td>
</tr>
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<td>PT13</td>
<td>PT14</td>
<td>PT15</td>
<td>PT16</td>
<td>PT17</td>
<td>PT18</td>
<td>PT19</td>
<td>PT20</td>
<td>PT21</td>
<td>PT22</td>
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<td>PT28</td>
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<td>PT58</td>
<td>PT59</td>
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<td>PT61</td>
<td>PT62</td>
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<tr>
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<td>+0.6</td>
<td>+0.5</td>
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<td>+0.7</td>
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<td>PT70</td>
<td>PT71</td>
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<tr>
<td>SoundPlan</td>
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<tr>
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<td>+1.6</td>
<td>+1.4</td>
<td>+1.8</td>
<td>+2.2</td>
<td>+1.9</td>
<td>+1.8</td>
<td>+1.9</td>
<td>+1.9</td>
<td>+1.8</td>
</tr>
</tbody>
</table>
Consequently, the model linked with the following numerical methods is applied in finding the best IL of the acoustical hood and the best parameters of the sound absorber for a multi-equipment system in the following section.

4. Case studies [9]

The noise abatement of one piece, two pieces, and three pieces of equipment, which are emitting broadband noises inside enclosed buildings, are demonstrated as the numerical cases. The restricted building area is 20 meters on the x-axis, 10 meters on the y-axis, and 5 meters on the z-axis. Three kinds of machine rooms with various pieces (1~3) of equipment and receiving points shown in Figs. 2~4 are applied in the optimal search. Both the acoustical panel and the acoustical enclosure are adopted to eliminate the machine room’s noise. The targeted noise level at the receivers is set at 100 dB(A). To efficiently obtain the optimal IL (Insertion Loss) and the design parameters of the acoustical panel, a minimization of Eqs. (14-18) in conjunction with the PSO method is used. The sound power level of the equipment A-C is shown in Table 3. In addition, the related coordinates of the equipment and the receivers are depicted in Table 4.
5. Particle swarm optimization [9]

PSO is an evolutionary computation technique developed by Kenney and Eberhart in 1995 [6]. The method has been developed through a simulation of simplified social models. PSO is based on swarms such as fish schooling and bird flocking. According to the research results, birds find food by flocking. The population consisting of individuals or particles is initialized randomly. Each particle is assigned a randomized velocity according to its own movement experience and that of the rest of the population. The problem solution space is formulated as a search space. Each particle position in the search space is a correlated solution to the problem. Particles cooperate to determine the best position (solution) in the search space (solution space). Understanding that the search space is $D$-dimensional and that there are $p$ particles in the swarm, we find particle $i$ is located at $\mathbf{X}_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$ and has a velocity $\mathbf{V}_i = (v_{i1}, v_{i2}, \ldots, v_{iD})$. Here, $i$ is 1 to $p$. On the basis of the PSO algorithm, each particle $i$ moves toward its own best position with $P_{\text{best}_i} = (p_{\text{best}_{i1}}, p_{\text{best}_{i2}}, \ldots, p_{\text{best}_{iD}})$. The best position of the whole swarm for each iteration $l$ is denoted...
As \( G_{\text{best}}^i = (g_{\text{best}}^i_1, g_{\text{best}}^i_2, \ldots, g_{\text{best}}^i_D) \). As indicated in Fig. 7, each particle changes its position according to its velocity which is randomly generated toward the \( p_{\text{best}} \) and the \( g_{\text{best}} \). For each particle \( i \) with dimension \((D)\), the next velocity \( V_{id}^{i+1} \) and position \( X_{id}^{i+1} \) is expressed as

\[
V_{id}^{i+1} = w \cdot V_{id}^i + c_1 \cdot \text{rand1} \cdot (p_{\text{best}}^i_{id} - X_{id}^i) + c_2 \cdot \text{rand2} \cdot (G_{\text{best}}^i - X_{id}^i) \tag{17}
\]

\[
X_{id}^{i+1} = X_{id}^i + V_{id}^{i+1} \tag{18}
\]

where \( l \) is the iteration number, \( w \), the inertial weight factor, is used to control exploration and exploitation. A large \( w \) value keeps the particles moving at a high velocity and prevents them from becoming trapped in the local optima. A small \( w \) value ensures a low particle velocity and encourages particles to exploit the same search area. The constants \( c_1 \) and \( c_2 \) are acceleration coefficients which determine whether particles prefer to move closer to the \( p_{\text{best}} \) or \( g_{\text{best}} \) positions. In this case, \( c_1 \) and \( c_2 \) are preset as 2. The \( \text{rand1} \) and \( \text{rand2} \) are two independent random numbers uniformly distributed between 0 and 1. The termination criterion of the \( PSO \) algorithm includes a maximum number of iterations (\( \text{Iter}_{\text{max}} \)). The flow diagram of the \( PSO \) process is depicted in Fig. 8.
6. Results and discussion [9]

6.1. Results

To reach a good optimization, three kinds of optimal PSO parameters, including particle population size \(p\), inertial weight factor \(w\), and maximal iteration number \(\text{Iter}_{\text{max}}\), are varied step by step during optimization. The results of the three optimizations (noise abatement for machine rooms with 1-3 equipment) — are described below.
6.1.1. CASE I: A machine room with one equipment

For a machine room with one piece of equipment, various sets of PSO parameters are tested during the optimal process. The simulated result optimized with respect to a broadband noise emitted from EQ.A is shown in Table 5. As indicated in Table 5, the optimal design data can be obtained when the PSO parameters at $p$, $Iter_{\text{max}}$, and $w = 500, 1000, 1.0$ are applied. The SPLs within the machine room before and after the noise abatement is performed are plotted in Fig. 9(A)(B). As revealed in Fig. 9(A)(B), the SPLs at RV.1 are 107 dB(A) and 100dB(A).

### Table 5. Optimal design parameters for a machine room with one piece of equipment at various PSO parameters.

<table>
<thead>
<tr>
<th>Item</th>
<th>PSO parameters</th>
<th>Design parameters</th>
<th>OBJ</th>
</tr>
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<td>$Iter_{\text{max}}$</td>
<td>$w$</td>
</tr>
<tr>
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<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
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<td>0.4</td>
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<tr>
<td>4</td>
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<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>400</td>
<td>100</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
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<td>500</td>
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</tr>
<tr>
<td>7</td>
<td>400</td>
<td>1000</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
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<td>1000</td>
<td>0.6</td>
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</tr>
<tr>
<td>11</td>
<td>400</td>
<td>1000</td>
<td>1.2</td>
</tr>
</tbody>
</table>
6.1.2. CASE II: A machine room with two equipment

By using the same PSO parameter set \((p, Iter_{\text{max}}, w) = (500, 1000, 1.0)\), the simulated result optimized with respect to two broadband noises emitted from EQ.A and EQ.B is shown in Table 6. The SPLs within the machine room before and after noise abatement is performed are plotted in Fig. 10(A)(B). As revealed in Fig. 10 (A)(B), the SPLs at RV.1 and RV.2 before noise abatement is performed are 108 dB(A); moreover, the SPLs at RV.1 and RV.2 after noise abatement is performed are 100dB(A).

**Table 6.** Optimal result for three machine rooms (CASE I–CASE III).

<table>
<thead>
<tr>
<th>Noise sources</th>
<th>Design parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>one equipment</td>
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</tr>
<tr>
<td>677</td>
<td>0.006</td>
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<tr>
<td>two equipment</td>
<td>RT1’</td>
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<tr>
<td>672</td>
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<tr>
<td>28.9</td>
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<td>RT15</td>
<td>RT16</td>
</tr>
<tr>
<td>29</td>
<td>10.9</td>
</tr>
</tbody>
</table>
6.1.3. CASE III: A machine room with three equipment

By using the above PSO parameters, the simulated results optimized with respect to three broadband noises emitted from EQ.A, EQ.B and EQ.C are shown in Table 6. The SPLs within the machine room before and after noise abatement is performed are plotted in Fig. 11(A)(B). As revealed in Fig.11 (A)(B), the SPLs at RV.1, RV.2, and RV.3 before noise abatement is performed are 120 dB(A); moreover, the SPLs at RV.1, RV.2, and RV.3 after noise abatement is performed are 100dB(A).

Figure 10. The SPL (at 1 meter from the ground) for a machine room with two pieces of equipment before and after noise abatement (A: before abatement; B: after abatement).

Figure 11. The SPL (at 1 meter from the ground) for a machine room with three pieces of equipment before and after noise abatement (A: before abatement; B: after abatement).
6.2. Discussion

Before the noise control is performed, the original SPLs within the three machine rooms (CASE I: a machine room with one piece of equipment, CASE II: a machine room with two pieces of equipment, CASE III: a machine room with three pieces of equipment) are shown in Figs. 9(A), 10(A), 11(A). Figs. 9(A)-11(A) indicate that the SPLs in CASE I-CASE III reach 107 dB(A), 108 dB(A), and 120 dB(A). In order to reduce the noise levels at the receivers (RV1-RV3), a targeted noise level of 100 dB(A) is specified. To achieve the targeted value, the objection functions (OBJ1~OBJ3) with respect to CASE I-CASE III used in summing the square of the SPL deviation at the receivers has been minimized using a PSO optimizer. As indicated in Table 5, to achieve a sufficient optimization in a machine room with one piece of equipment, the selection of an appropriate PSO parameter set is essential. Using the PSO sets in the optimization process, the best SPL with respect to the three machine rooms that have added acoustical enclosures onto the EQ1-EQ3 has been shown in Table 6. As indicated in Table 6, the sound insertion loss of the acoustical enclosures tends to increase if the equipment existing in the enclosed machine room is increased. Consequently, as depicted in Figs. 9(B), 10(B), and 11(B), the resultant SPLs at the receivers can almost reach 100 dB(A) with respect to three kinds of numerical cases (CASE I-CASE III).

7. Conclusion [9]

Three kinds of machine rooms (CASE I: a machine room with one piece of equipment, CASE II: a machine room with two pieces of equipment, CASE III: a machine room with three pieces of equipment) are shown in Figs. 2-4. There are two primary sound energies within the enclosed room, one is the direct sound wave emitted from the EQ1-3, and the other is the reverberant sound wave reflected from the walls. In order to efficiently depress the noise levels at the receivers (RV1-RV3), a one-layer acoustical panel attached on the walls and ceiling used to eliminate the reflected sound energy and an acoustical enclosure used to reduce the direct sound wave emitted from the equipment are required. Based on the targeted SPL (100dB(A)) at the receivers (RV1-RV3), a numerical assessment using a PSO optimizer for the appropriate acoustical panel design as well as the acoustical enclosures in CASE I-III is performed. Results reveal that to achieve a sufficient optimization in a machine room with one piece of equipment, the selection of an appropriate PSO parameter set is crucial. Using the PSO sets in the optimization process, the best SPL with respect to
the three machine rooms that have added acoustical enclosures onto the EQ.1-EQ3 is shown in Table 6. As indicated in Table 6, the sound insertion loss of the acoustical enclosures will increase if the equipment in the enclosed machine room increases. Consequently, as depicted in Figs. 9-11, the receivers’ SPLs with respect to three kinds of numerical cases (CASE I~CASE III) can be improved by 7 dB(A), 8 dB(A), and 20 dB(A).

8. Nomenclature

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

- \( C_o \): sound speed (m s\(^{-1}\))
- \( dH \): diameter of perforated hole on the front plate (m)
- \( L_o \): constrained total thickness of the acoustical panel (m)
- \( D_f \): thickness of the acoustic fiber (m)
- \( f \): cyclic frequency
- \( \text{Iter}_{\text{max}} \): maximum number of iteration
- \( K_{\text{fiber}} \): complex propagation constant of the acoustic fiber
- \( K_p \): complex propagation constant of the perforated front plate
- \( K_{14} \): real part of complex \( K_{\text{fiber}} \)
- \( K_{24} \): image part of complex \( K_{\text{fiber}} \)
- \( L \): air depth of the acoustical panel (m)
- \( m \): surface density of the perforated front plate per 1m\(^2\) (kg m\(^{-2}\))
- \( N \): hole’s number on the perforated front plate per 1m\(^2\)
- \( OBJ \): objective function
- \( p \): number of particles
- \( P \% \): perforated ratio of the perforated front plate (%)
- \( p_i \): acoustic pressure at \( i \) (Pa)
- \( Q \): thickness of the perforated front plate (m)
- \( R_f \): acoustic flow resistivity of the acoustic fiber (MKS rayls m\(^{-1}\))
- \( R_{\text{fiber}} \): real part of complex \( Z_{\text{fiber}} \)
- \( u_i \): acoustic particle velocity at \( i \) (kg s\(^{-1}\))
\( w \): inertial weight

\( Z_i \): specific normal impedance at \( i \).

\( Z_{fiber} \): characteristic impedance of the acoustic fiber

\( Z_p \): characteristic impedance of the perforated front plate

\( X_{fiber} \): imaginary part of complex \( Z_{fiber} \)

\( \alpha \): sound absorption coefficient of absorber

\( \omega \): angular frequency (rad s\(^{-1}\))

\( \rho_o \): air density (kg m\(^{-3}\))

**Reference**