Research Article

Optimization of Screw Mufflers Equipped with Two Inlets and One Outlet Using Neural Network Model, Finite Element Method, and Genetic Algorithm

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Noise abatement by using efficient mufflers is compulsory, as venting noise, a type of huge noise in the industry, has a serious impact on human hearing. In order to reduce the noise abatement cost, the idea of using a muffler to suppress two kinds of venting noise sources arises. In this study, a muffler internally inserted with a screwed plate was proposed with two inlets and an outlet for exhaust venting. An analysis of the finite element method (FEM) was performed to estimate the muffler’s acoustical performance using the COMSOL program. A simplified objective function established by an artificial neural network (ANN) was trained to shorten the optimization procedure and linked to a genetic algorithm (GA). During the muffler analysis, both Rx (the outline dimension of the muffler) and D (the diameter of a straight and perforated tube) were chosen as design parameters. In addition, two target frequencies (1500 Hz and 2000 Hz) were specified during the optimization process. Consequently, the result reveals that the optimization of a screw muffler having two inlets and one outlet was efficiently assessed.

1. Introduction

Sound absorbing wool and acoustical tube are commonly used as essential materials in noise abatement. Concerning the research of acoustical wool, Delany and Bazley [1] analyzed the sound absorption coefficient for acoustical wool in 1969. Johnson et al. [2], in 1987, continued to investigate the sound absorption coefficient using acoustical flow resistance, porosity, curvature, and viscous characteristics length. In addition, Champoux and Allard [3], in 1991, explored the sound absorbing property using a new parameter of thermal characteristics length. Lafarge et al. [4] developed a Johnson-Champoux-Allard model to evaluate the sound absorbing coefficient in 1995.

Regarding the research of curved acoustical duct, Cummings [5] assessed the acoustical performance of curved tube equipped with various sections (rectangular and circular) in 1974. Rostafinski [6] developed a model to analyze the sound propagation within a curved duct in 1974. In 1978, Fuller and Bies [7, 8] tried to improve the acoustical performance by adjusting the duct shape and section area. In 1999, Kim and Ih [9] used a four-pole matrix to estimate the sound transmission loss of a curved expansion chamber. As mentioned above, both the curve-shaped tube and acoustical wool have a great influence in the noise elimination.

2. Research Gate

Mufflers have been customarily used in dealing with venting noise. Studies on muffler optimization were focused on the use of plane wave theory which is valid below the cutoff frequency, a low frequency depending on the
muffler’s geometry [10–12]. However, the muffler mechanism mentioned above is simple, and the acoustical performance in a high-order sound wave is ignored. A muffler with a complicated mechanism is required for better acoustical performance. Considering the high-frequency effect for a muffler with a complicated acoustical mechanism, an FEM simulation was thus adopted for acoustical simulation [13–16]. While dealing with the optimization issue, Bhunia and Sahoo assessed the reliability optimization in an interval environment by genetic algorithm [17]. Mahato et al. optimized system reliability for serial system with fuzzy component reliabilities using a genetic algorithm [18]. Sahoo et al. used an efficient muffler to reduce the multiple noises. Here, a muffler composed of the efficient acoustical element and hybridized with two inlets and one outlet is proposed to develop an efficient muffler at a low cost.

3. Motivation and Novelty

In the real world, there are many venting noise sources in chemical industries. For the economic purpose, an idea of using one muffler to simultaneously reduce two venting noise sources arises. Therefore, a muffler composed of the screwed shell (an efficient acoustical element) and hybridized with two inlets and one outlet is proposed to develop an efficient muffler to reduce the multiple noises. Here, a muffler with two inlets was connected to two noise sources to direct the venting sound waves into the muffler, before the exhaust was vented through a single outlet. The muffler proposed in this study was optimized by applying the artificial neural network (ANN) and GA method. In addition, two target frequencies (1500 Hz and 2000 Hz), which are very sensitive to human hearing, were also specified during the muffler optimization.

4. Theoretical FEM Model (on COMSOL)

As indicated in Figure 1, a muffler internally inserted by a screwed shell and hybridized with two inlets and one outlet was introduced. The acoustical boundary condition of a solid boundary analyzed in the acoustical model of COMSOL is

\[ n \cdot \left( \frac{1}{\rho} \left( \nabla p_t - q \right) \right) = 0, \]  \hspace{1cm} (1)

where \( q \) is a dipole sound source, \( c \) is the sound speed, and \( \rho \) is the air density and are set at zero, 343 (m/s), and 1.293 (kg/m^3), respectively.

The acoustical boundary condition of the perforated tube (a solid boundary) analyzed in the COMSOL model is

\[ n \cdot \left( \frac{1}{\rho} \left( \nabla p_t - q \right) \right) = -(p_{1i} - p_{2i}) \frac{i \omega}{Z_i}, \]  \hspace{1cm} (2)

\[ Z_i = \rho_c \cdot c \left[ \frac{1}{\rho} \frac{8 \mu k}{\rho_c c} \left( 1 + \frac{t_p}{\delta_h} \right) + \theta_j + i \frac{k}{\sigma} (t_p + \delta_h) \right] \]  \hspace{1cm} (3)

Using the Johnson-Champoux-Allard model, the analysis of the acoustical behavior of porous acoustical wool yields

\[ \rho_{\text{eff}} = \alpha_{\text{con}} \rho_0 \left( 1 + \frac{\sigma_0 \phi}{j \rho_0 \omega \alpha_{\text{con}}} G_j(\omega) \right), \]  \hspace{1cm} (4)

\[ G_j(\omega) = \left( 1 + \frac{4 j \alpha^2 \sigma_0 \phi}{\sigma_0 G J^2 \phi^2} \right)^{1/2}, \]  \hspace{1cm} (5)

where \( \alpha_{\text{con}} \) is the shearing viscosity, \( \eta \) is the curvature level, and \( \phi \) is the porosity of the material, and \( \sigma_0 \) is the flowing impedance expressed as follows:

\[ \sigma_0 = \frac{\mu}{\alpha} = \frac{150 \mu (1 - \phi)^2}{D \phi^2}. \]  \hspace{1cm} (6)

In addition, the bulk factor (\( K_{\text{eff}} \)) yields

\[ K_{\text{eff}} = \frac{y P_0}{y - (y - 1) \left( 1 + \frac{8 \eta \Lambda^2}{B^2} \right) \left( 1 + j \rho_0 w B^2 \Lambda^4 / 16 \eta \right)^{1/2}}. \]  \hspace{1cm} (7)

The viscous character length (\( \Lambda \)) and thermal character length (\( \Lambda' \)) are

\[ \Lambda = \frac{1}{c} \left( \frac{8 \alpha \eta}{\alpha_{\text{con}} \phi} \right)^{1/2}, \]  \hspace{1cm} (8)

\[ \Lambda' = \frac{1}{c'} \left( \frac{8 \alpha \eta}{\alpha_{\text{con}} \phi} \right)^{1/2}. \]  \hspace{1cm} (9)

The governing equation of the sound wave propagating inside the muffler is

\[ \nabla \cdot \left( \frac{1}{\rho_c} (\nabla p_t - q) - \frac{k_{eq}^2 p_t}{\rho_c} \right) = Q, \]  \hspace{1cm} (10a)

where

\[ p_t = p + p_b; \quad k_{eq}^2 = \left( \frac{\omega}{c_c} \right)^2; \quad c_c = c; \quad \rho_c = \rho. \]  \hspace{1cm} (10b)

The acoustical transmission loss (TL) is

\[ TL = 10 \log \frac{W_{\text{in}}}{W_{\text{out}}}. \]  \hspace{1cm} (11)

5. Model Check

Before the shape was optimized, the FEM analysis by COMSOL was checked for correctness based on experimental data and
other theoretical data. For a muffler hybridized with a straight and perforated tube, the simulated TL verified by experimental data [23] was proved to be acceptable, as indicated in Figure 2. In addition, as exemplified in Figure 3, the simulated TL of a muffler having two inlets and one outlet was similar to the theoretical data by the green solution method [24]. Therefore, the FEM model was correct. The acoustical simulation of the muffler using the FEM is performed in the following section.

6. Artificial Neural Network Model

The mathematical function of ANN was implicit when using the hidden layers inside the ANN structure, which was inconvenience during calculation. Therefore, an explicit form using a polynomial neural network was compulsory. As seen in Ivakhnenko’s research [25], the relationship between the neurons’ layers was shortened, thus allowing an easy weight adjustment and assessment of the factors of the polynomial functions when the polynomial neural network was adopted with a regression process. The polynomial neural network illustrated in Figure 4 includes an input layer, a hidden layer, $\Sigma$ (summation), and an output layer (product).

For $h$’s unit number of the hidden layer, the neural network’s output is

$$y_k = \prod_{j=0}^{h} \sum_{i=1}^{n} W_{ij} X_{ij}, \quad (12)$$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The mechanism of a screw muffler equipped with two inlets and one outlet.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Accuracy check of sound transmission loss for mufflers internally inserted with a straight and perforated tube [23].}
\end{figure}
Developing equation (12) yields

\[ y_k = B_0 + \sum_{i=1}^{n} B_i x_i + \sum_{i=1}^{n} \sum_{j=1}^{n} B_{ij} x_i x_j \]

\[ + \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{k=1}^{n} B_{ijk} x_i x_j x_k + \cdots, \tag{13} \]

where \( x_i, x_j, x_k \) are the input data, \( y_k \) is the output value, and \( B_0, B_i, B_{ij}, \) and \( B_{ijk} \) are the node function factors.

The ANN model was trained by importing the training data bank of the muffler’s parameters and theoretical TL calculated by the COMSOL. The polynomial together with the PSE standard was also calculated. The PSE, a mean square’s deviation, yields

\[ \text{PSE} = \frac{1}{NN} \sum_{i=1}^{NN} (\tilde{y}_i - y_i)^2 + \text{CPM} \frac{2\sigma^2 QQ}{NN}, \tag{14} \]

where \( \sigma^2 \), CPM, and QQ represent the error variation, the product of the penalty function, and the number of the network factors, respectively. \( NN \), \( \tilde{y}_i \), and \( y_i \) are the number of training data, data required by ANN, and data predicted by the model, respectively. The related TL was predicted by substituting an arbitrary value of the muffler’s geometrical data (design data) into the trained ANN model. The muffler was then optimally shaped using the ANN model (simplified OBJ function) and the genetic algorithm.

7. Genetic Algorithm

Holland [26] developed a genetic algorithm (GA) according to the concept of Darwinian natural selection. Later, Jane [27] extended the GA theory in practical application. Thanks to the excellent ability in searching for the optimal solution, the application of GA was prosperously developed. In previous studies [28, 29], GA was adopted in solving engineering’s space-constrained problem.

Seven control parameters were chosen for GA in the optimization process for the purpose of the study. The GA’s control parameters are gene population (pop), a length of chromosome (bit), a selection strategy (elitism), a mutation ratio (pm), a crossover ratio (pc), and a maximum iteration \( \text{iter}_{\text{max}} \).

Each pair of candidate parents was chosen by using the coding and decoding process in conjunction with the simplified OBJ function. The precision of the parameter search (MM) is

\[ \text{MM} = \frac{P_{\text{max}} - P_{\text{min}}}{N_p - 1}, \tag{15} \]

where \( P_{\text{max}} \) and \( P_{\text{min}} \) are the parameters’ maximum and minimum ranges, respectively. \( N_p \) is calculated as \( 2^m \), where \( m \) is the number of muffler parameters. The related GA optimization process is illustrated in Figure 5. As seen in Figure 5, the optimization procedure terminated when the generation number reached \( \text{iter}_{\text{max}} \).

8. Sensitivity Analysis

As indicated in Figure 6, R, an acoustical flowing resistance, has been selected as a design parameter in the sensitivity analysis. The simulation result shown in Figure 7 reveals that the TL increased with R. Similarly, as depicted in Figure 8, considering that the muffler was lined with acoustical wool of 500 kg/m\(^3\).s internally, \( \sigma \) (the perforation ratio of a straight and perforated tube in muffler) was chosen as a
design parameter. The simulation result is plotted in Figure 9. As observed in Figure 9, the fluctuation of TL below the frequencies of 1000 Hz was not obvious as the $\sigma$ value varied. Moreover, the Rx (the outline diameter of the muffler) was also selected as a design parameter and is depicted in Figure 10. The impact of TL with regard to Rx was captured and is illustrated in Figure 11. As shown in Figure 11, the fluctuation of TL at the frequency of 300 Hz above was obvious as the value of Rx varied. Subsequently, as depicted in Figure 12, the D (the diameter of the straight and perforated tube) was selected as a design parameter. The effect of TL related to D was investigated and is shown in Figure 13. As seen in Figure 13, the fluctuation of TL was roughly clear when the value of D varied.

9. Case Study

A muffler with a screwed shell inside was presented in order to enhance the acoustical efficiency of the muffler used to depress the venting noise. In addition, a concept of two inlets was also adopted in the muffler design for the cost-saving purpose.

As mentioned in section 6, the effect of TL with regard to four kinds of geometric factors, including R, $\sigma$, D (the diameter of a straight and perforated tube within the muffler), and Rx, was assessed. The results in Figures 7, 9, 11, and 13 indicate that the TL was proportional to R. The tendency of TL with respect to $\sigma$ was trivial and not clear. The fluctuation of TL with respect to Rx and D was large. Therefore, the
geometrical design data of Rx and D shown in Figure 14 were then chosen as a design parameter in the muffler optimization.

The parameters’ range and schedule levels are illustrated in Table 1. The simulated TL in relation to sixteen training data sets is depicted in Table 2. With Rx and D as the input data and the TL (simulated by COMSOL) as the output data, the ANN model was established via a training process and testing process. The ANN model, a simplified objective function, regarding the specified frequencies of 1500 Hz and 2000 Hz was obtained and is listed as follows.

9.1. Target Frequency—1500 Hz

\[
\begin{align*}
N_{1,1500} &= -7.36122 + 0.866025 \times D, \\
N_{2,1500} &= -35.9401 + 0.866025 \times Rx, \\
N_{3,1500} &= -0.40494 - 0.205475 \times N_{2,1500}^2 + 0.43198 \times N_{2,1500}^2 - 0.409656 \times N_{2,1500}^3, \\
N_{4,1500} &= -0.835321 + N_{2,1500}^2.
\end{align*}
\]
\[ N_{51500} = 1 \times N_{31500} - 0.317515 \times N_{31500} \times N_{11500} + 0.151953 \times N_{31500} \times N_{41500} \times N_{11500} \]  
\[ T_{L_{1500}} = 14.4171 + 7.70476 \times N_{5_{1500}} \]  

9.2. Target Frequency—2000 Hz

\[ N_{12000} = -7.36122 + 0.866025 \times D, \]  
\[ N_{22000} = -35.9401 + 0.866025 \times R_x, \]
10. Results and Discussion

10.1. Results. The design parameters of Rx and D at target frequencies (1500 Hz and 2000 Hz) were optimized by utilizing the trained ANN model together with the GA method. The GA control parameters adopted in the study are provided in Table 3. The comparison of design data sets (before and after optimization at targeted frequencies of 1500 Hz and 2000 Hz) is shown in Tables 4–5. The accuracy of TL predicted by the ANN model was also verified by the exact solution run on the COMSOL. As indicated in Tables 6–7, the accuracies of the ANN model at 1500 Hz and 2000 Hz were 17.9% and 12.8%, respectively.
Table 3: The genetic algorithm’s control parameter set used in the GA optimization process.

<table>
<thead>
<tr>
<th>GA control parameter</th>
<th>Value or strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>Generated random</td>
</tr>
<tr>
<td>Crossover</td>
<td>Uniform crossover</td>
</tr>
<tr>
<td>Elitism</td>
<td>Open</td>
</tr>
<tr>
<td>Selection strategy</td>
<td>Elitism</td>
</tr>
<tr>
<td>Itermax</td>
<td>1000</td>
</tr>
<tr>
<td>Bit</td>
<td>20</td>
</tr>
<tr>
<td>Pop</td>
<td>100</td>
</tr>
<tr>
<td>Pc</td>
<td>0.6</td>
</tr>
<tr>
<td>Pm</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 4: The comparison of related design parameters before and after optimization at 1500 Hz.

<table>
<thead>
<tr>
<th>Design parameter (mm)</th>
<th>Rx</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before optimization</td>
<td>400</td>
<td>70</td>
</tr>
<tr>
<td>After optimization (at 1500 Hz)</td>
<td>421.7</td>
<td>74.8</td>
</tr>
</tbody>
</table>

Table 5: The comparison of related design parameters before and after optimization at 2000 Hz.

<table>
<thead>
<tr>
<th>Design parameter (mm)</th>
<th>Rx</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before optimization</td>
<td>400</td>
<td>70</td>
</tr>
<tr>
<td>After optimization (at 2000 Hz)</td>
<td>406.2</td>
<td>76.3</td>
</tr>
</tbody>
</table>

Table 6: Accuracy check between the ANN model and COMSOL (optimal design set at 1500 Hz).

<table>
<thead>
<tr>
<th>TL (optimal design parameter set at 1500 Hz) obtained by ANN in conjunction with GA</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.53</td>
<td>17.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TL (optimal design parameter set at 1500 Hz) calculated by COMSOL</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>39.02</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Accuracy check between the ANN model and COMSOL (optimal design set at 2000 Hz).

<table>
<thead>
<tr>
<th>TL (optimal design parameter set at 2000 Hz) obtained by ANN in conjunction with GA</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.19</td>
<td>12.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TL (optimal design parameter set at 2000 Hz) calculated by COMSOL</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>21.97</td>
<td></td>
</tr>
</tbody>
</table>

By substituting the original data and the optimal design data into the COMSOL’s calculation, the theoretical TL profiles (before and after optimization) are illustrated in Figures 15–16. As illustrated in Figure 15, the TLs at the targeted frequency of 1500 Hz before and after executing the optimization were 16.0 dB and 39.0 dB, respectively.

Moreover, as depicted in Figure 16, the TLs at the specified frequency of 2000 Hz before and after optimization were 9.7 dB and 21.9 dB, respectively.

10.2. Discussion. As seen in section 8, the effect of the TL with regard to the geometric data of R, Rx, and D was significant. The tendencies of the TL with respect to Rx and D were oblique. However, the fluctuation of TL with respect to Rx and D was obvious. Therefore, both the Rx and the D were then chosen as the design parameters during the optimization procedure in order to find appropriate design data.

The numerical assessment of the muffler using ANN along with the GA method was performed. The simulation results were obtained and are shown in Tables 6–7 and Figures 15–16. The noise abatement of the muffler at the target tones of 1500 Hz and 2000 Hz was improved by 23 dB.
and 12.2 dB, respectively, when using the optimization process. Moreover, the accuracy between the ANN model and the FEM shown in Tables 6–7 was between 12.8% and 17.9%.

11. Conclusion

A screw muffler internally inserted with a screwed shell and hybridized with two inlets and one outlet was introduced to advance the acoustical efficiency of the muffler. In addition, the result of sensitivity analysis indicates that $R$, $R_x$, and $D$ had a significant influence on the muffler’s acoustical efficiency. Here, the TL is relational to the $R$ value, but the tendencies of TL with respect to $R_x$ and $D$ were not clear. In order to purchase a best design data for the muffler, the optimization using $R_x$ and $D$ as the design parameters was necessary. The trained neural network (ANN) model was adopted and served as a simplified objective function for the muffler optimization. The muffler optimization applying the ANN model in combination with the GA method was then performed. Simulation results in this study reveal that the TLs at the target frequencies of 1500 Hz and 2000 Hz were improved by 23 dB and 12.2 dB.

Abbreviations

- $bit$: Chromosome’s bit length
- $B_0$, $B_1$, $B_p$: The coefficients of the ANN’s node function
- $B_{ijk}$: The product of the penalty function
- $CPM$: The number of design parameters
- $D$: The diameter of the straight and perforated tube (m)
- $iter_{max}$: The number of maximum iterations in GA processing
- $m$: The number of design parameters
- $MM$: The precision of the parameter search
- $NN$: The number of training data sets
- $N_p$: The possible number for searching ($=2^m$)
- $P_c$: The ratio of crossover
- $P_m$: The ratio of mutation
- $P_{max}$: The parameter’s maximum range
- $P_{min}$: The parameter’s minimum range
- $pop$: The population number
- $R$: Acoustical impedance of acoustical wool (kg/m$^2$s)
- $R_x$: Outline diameter of the screw muffler (m)
- $x_i$, $x_j$, $x_k$: The ANN’s input data
- $y_i$: The ANN’s output value
- $y_j$: The required data in the ANN
- $y_k$: The predicted data for the ANN
- $TL$: Transmission loss (dB)
- $\sigma$: Perforation rate of a perforated tube (%)
- $\sigma_p$: The ANN’s error variation.

Data Availability

We already include all the data in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


