# Design of a Circular-type Pod Silencer for a High-pressure Axial Flow Fan

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Abstract: A circular-type pod silencer has been designed to reduce a high noise level generated from an axial flow fan. The noise consists of two components such as discrete frequency noise component at blade passing frequency due to rotating impellers and broadband noise component due to turbulence produced in the axial fan. Main contribution into the high noise level is due to the discrete frequency noise component. In order to effectively reduce the noise level of the axial flow fan, the circular-type pod silencer has been modelled in this paper. In order to identify critical design parameters, finite element analysis (FEA) with commercial ANSYS acoustic code was implemented. The results of the design parametric study have been used to design the circular-type pod silencer that effectively reduces the high noise level of the axial flow fan in subway ventilation system.

## 1 INTRODUCTION

Axial flow fans are widely used in low pressure air handling systems such as cooling, air-conditioning, or ventilating equipment (Dixon, 2014). But subway ventilation systems require axial flow fans with relatively high pressure at high flow capacity. Those generate high noise level. The noise consists of two components such as discrete frequency noise component at blade passing frequency (BPF) due to rotating impellers and broadband noise component due to turbulence in inflow and exhaust jet mixing (Lee and Kil, 2018). Main contribution into the high noise level is due to the discrete frequency noise component. It is needed to attach silencers to reduce the high noise level. Rectangular silencers in subway ventilation systems have been widely used. But those silencers generate relatively high pressure loss. Therefore, there have been industrial needs for reducing high noise level with circular-type pod silencers effective to axial flow fan performance with lower pressure loss.

The circular-type pod silencer was analyzed by using transfer matrix method with plane wave approximation (Munjal, 2003). Multimode sound propagation was used to analyze the circular-type pod silencer (Kirby, 2006). FEA approach was implemented to analyze dissipative silencers (Peat and Rathi, 1995; Mehdizadeh and Paraschivoiu, 2005; Cui et al., 2014). The design curves for performance evaluation of passive pod silencers were provided by simulating the acoustic performance of the silencers with commercial FEA software (Ramarkrishnan, 2015). Practical design of the circular-type pod silencer have been widely performed experimentally or based on existing experimental results and design curves in reference (Ver and Beranek, 2006). In this paper, in order to reduce the high noise level of an axial flow fan in a subway ventilation system, design of the circular-type pod silencer has been performed with FEA simulation using commercial ANSYS acoustic code (ANSYS, 2019). The transmission loss of the silencer was evaluated by solving the three-dimensional sound wave equation inside the silencer. The design parametric study has been performed to identify critical design parameters. It has been implemented to design the circular-type pod silencer that effectively reduces the high noise level of the axial flow fan in the subway ventilation system.



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# 2 THEORY

## 2.1 Sound Transmission Loss and Insertion Loss

In order to reduce the noise generated from the axial flow fan, a silencer is attached to the fan. The noise attenuation performance of the silencer is evaluated in terms of transmission loss (TL) and insertion loss (IL).

TL is defined as the logarithmic ratio between the incident sound power $W_i$ at the inlet of the muffler and the transmitted sound power $W_t$ at the outlet of the silencer in Figure 1 as

$$\mathrm{TL} = 10\, log_{10} \frac{W_i}{W_t}. \quad (1)$$

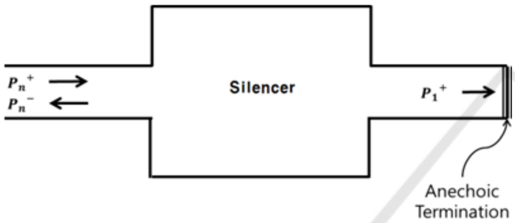


Figure 1: Layout for evaluation of transmission loss.

If the area of the inlet is the same as the area of the outlet, TL can be experessed with complex amplitude of the incident pressure $P_n$ and complex amplitude of transmitted pressue $P_1$ as

$$\mathrm{TL} = 10\, log_{10} \frac{|P_n^2|}{|P_1^2|} \quad (2)$$

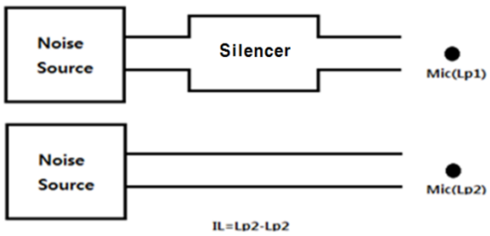


Figure 2: Layout for evaluation of insertion loss.

IL is defined as the difference between sound power level $Lp_2$ at the termination without the silencer and sound power level $Lp_1$ at the termination with the silencer installed as shown in Figure 2. In the case of IL, it is not necessary to install an anti-reflection terminal as shown in Figure 2. Thus it is closer to an actual value of noise attenuation because all actually installed connectors related to the fan and the silencer are considered.

If the cross-sectional area of the inlet is equal to the cross-sectional area of the outlet and the outlet is anti-reflected, TL and IL become equal. Assuming this condition, TL has been considered to design the silencer in this paper.

## 2.2 Finite Element Analysis

Numerical simulation methods play an increasingly important role in the design of silencers as well as other noise and vibration applications. FEA offers an advantageous combination of modelling flexibility, computational efficiency and result accuracy. Comparing to the boundary element analysis (BEA), FEA allows modelling more complex physics of acoustics considering multiple fluid domains, sound propagation in a mean flow and effects of temperature gradients in a fluid medium. FEA can be especially used to design of the silencers to reduce relatively high frequency noise considering the higher modes above the cut-off frequency for the plane wave approximation as well as to design the silencers with relatively complex shapes.

(a) (b)

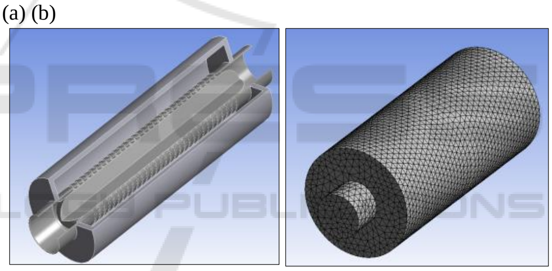

Figure 3: (a) Structural shape and (b) finite element model of an circular-type pod silencer.

The linear wave equation for perfect gas with no damping is expressed in terms of pressure $p$ and speed of sound $c$ as

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial^2 t} \quad (3)$$

At each frequency in the interested frequency range that equation (3) becomes Helmholz's equation as

$$\nabla^2 P = -k^2 P \quad (4)$$

where $P$, $k$ mean complex pressure amplitude and the acoustic wavenumber at the given frequency, respectively. The three dimensional acoustic domain of the silencer in Figure 3(a) is divided into elements in Figure 3(b). The variational formulation of the silencer problem allows to formulate the discretized equation of linear systems of algebraic equations as

$$[\mathrm{A}]\{P\} = \{f\} \quad (5)$$

where [A], $\{P\}$ and {f} are the coefficient matrix, sound pressure amplitude vector of nodal values and forcing function vector of nodal values, respectively. In the present silencer problem, {f} is only a non-zero value at the inlet pipe according to Dirichlet boundary condition with unit pressure.

In this study, FEA is performed with a commercial FEA program ANSYS. For more efficient way to model perforation of the silencer, meshes on the perforated tube are replaced by the two inner and outer concentric surfaces with acoustic transfer admittance. For the acoustic transfer admittance, the transfer admittance of the perforated plate (Mechel, 2008) with the same perforation pattern of the perforation tube is used. Another effective method is to use equivalent fluid model to model sound absorbing materials in the silencer. In this work Miki equivalent fluid model (Miki, 1990) has been implemented, that uses the following expressions for the complex characteristics impedance $Z_c$ and complex wavenumber $k$ of the sound absorbing material at frequency $f$ as

$$Z_c = \rho_0 c_0 \left[ 1 + 5.50 \left( 10^3 \frac{f}{R} \right)^{-0.632} - j\, 8.43 \left( 10^3 \frac{f}{R} \right)^{-0.632} \right] \tag{6}$$

$$k = \frac{2\pi f}{c_0} \left[ 1 + 7.81 \left( 10^3 \frac{f}{R} \right)^{-0.618} - j\, 11.41 \left( 10^3 \frac{f}{R} \right)^{-0.618} \right] \tag{7}$$

Here $\rho_0, c_0$ and $R$ correspond to air density, speed of sound and fluid resistivity of the sound absorbing material, respectively. It is known that Miki equivalent fluid model is regarded valid in the frequency range of $f/R < 0.01$. .

# 3 ANALYSIS

## 3.1 Noise Characteristics Analysis

The noise source considered in this research is an axial flow fan (Figure 4) operating with high pressure rise at high flow capacity in the subway ventilation system. It generates high noise level. The noise consists two kinds of noise components such as discrete frequency noise at BPF and the broadband noise distributed over wide frequency range. BPF noise is produced mainly due to rotating steady fan blade thrust and blade interaction. Broadband noise is produced over entire frequency range due to turbulent boundary layer on blade surface, inflow turbulence and blade wake. Figure 5 shows the typical pattern of noise spectrum measured from the regenerative blower. Here BPF corresponds to 198 Hz.

Figure 4: Axial flow fan.

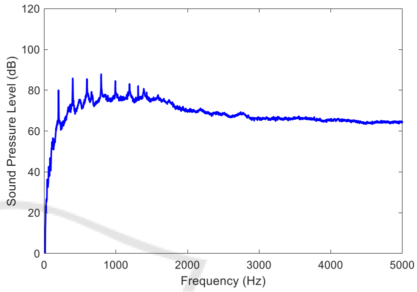


Figure 5: Measured noise spectrum of axail flow fan.

## 3.2 Verification of Analysis

In order to verify the FEA simulation approach, FEA has been applied to evaluate TL of silencer models in reference (Beranek, 2006). The silencer models are circular-type silencer without a pod, circular-type silencer with a rigid pod and circular-type silencer with sound absorbing pod ( $R = 16{,}000\ Ns/m^4$ ). Those have dimensions as $h = 0.15\text{m}, D_p = 0.3m, d = 0.2m$ and $L = 1.2\text{m}$ as shown in Figure 6.

The predicted numerical results for TL have been compared with the corresponding results in the reference (Beranek, 2006) as shown in Figure 7. It showed that FEA approach can be used to evaluate TL of the circular-type pod silencers in good agreement with the experiment results in the reference.

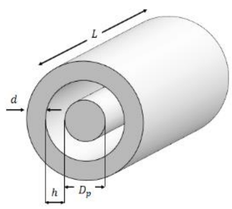


Figure 6: Silencer models for analysis verification.

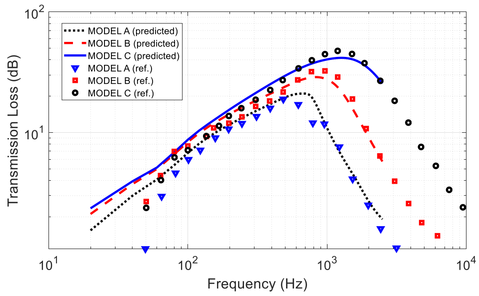


Figure 7: Comparison of the predicted TL of silencers (without a pod [model A], with a rigid pod [model B] and with an sound absorbing pod [model C], respectively) with results in the reference.

### 3.3 Tl Characteristics

The design model is the circular-type pod silencer as shown in Figure 8. The outer surface of the sound absorbing pod and the inner surface of the outer sound absorbing layer are formed of perforated tubes. The design variables are outer diameter $D_0$, inner diameter $D_i$, sound absorbing pod diameter $D_p$, air flow gap thickness $h$, sound absorbing outer layer thickness $d$, type of sound absorbing material, density of sound absorbing material and porosity σ of perforated tubes. Considering a flame retarding material, glass wool is selected as the type of the sound absorbing material.

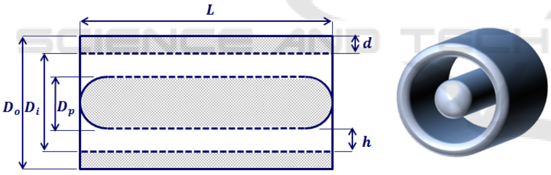


Figure 8: Design model of the circular-type pod silencer.

The design parametric study was performed by evaluating TL. Figures 9-11 show the influence of changing corresponding design variable on TL of the silencer. Figure 9(a) shows little influence of changing the thickness of the absorbing outer layer on TL if it is more than about 0.2 m. Figure 9(b) shows that the air flow gap thickness decreases, TL increases in all frequency region and the frequency at which the maximum TL value occurs also increases.

Figure 10(a) shows that the length of the silencer increases, the TL value increases in the main noise reduction frequency band. Figure 10(b) shows that the pod diameter increases, TL also increases in the main noise reduction frequency band.

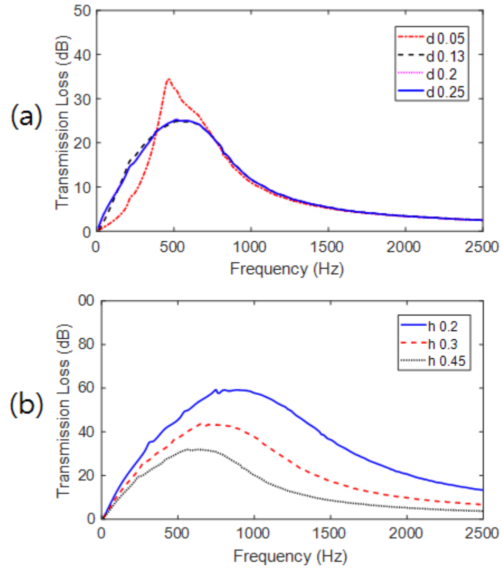


Figure 9: Influence of corresponding design variable change on TL of the silencer as (a) outer sound absorbing layer thickness, (b) air flow gap thickness.

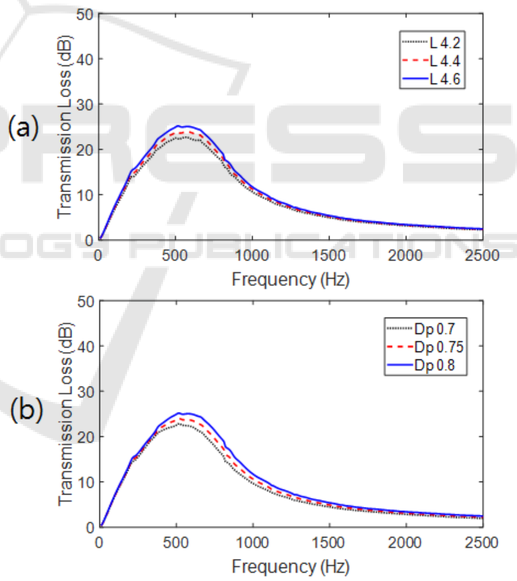


Figure 10: Influence of corresponding design variable change on TL of the silencer as (a) silencer length and (b) sound absorbing pod diameter.

Figure 11(a) shows that the density of the sound absorbing material increases, the main noise reduction frequency band increases but the maximum TL value decreases. Figure 11(b) shows little influence of changing the porosity of the perforated tube on TL, if it is more than about 46.2 %. The parametric study results show that the most sensitive design parameter corresponds to the air flow gap thickness.

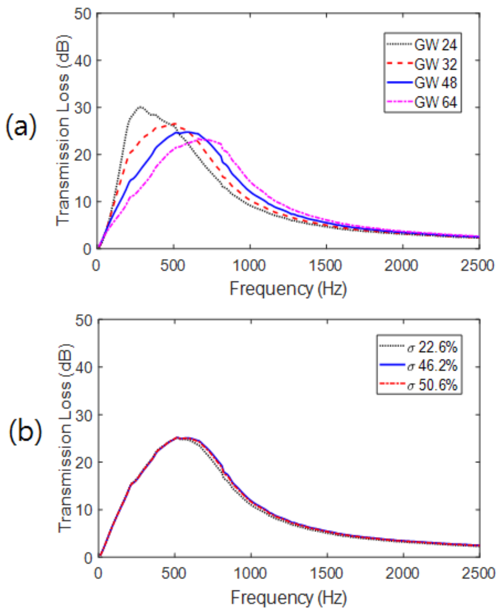


Figure 11: Influence of corresponding design variable change on TL of the silencer as (a) sound absorbing material density in unit of $kg/m^3$ and (b) porosity of the perforated tubes.

# 4 RESULTS

In order to design the circular-type pod silencer, the silencer installation space condition in subway provides constraints as $D_0 \leq 3.3\ m$ and $L \leq 4.3m$. Considering the fan casing inner diameter $1.8\ m$ of the axial flow fan, constraint as $D_i \geq 1.8\ m$ is also given.

Table 1: Specifications of the designed circular-type pod silencer.

| Design Variables | Value |
|---|---|
| air flow gap $h$ | 0.4 m |
| sound absorbing outer layer thickness $d$ | 0.25 m |
| outer diameter $D_0$ | 2.3 m |
| inner diameter $D_i$ | 1.8 m |
| pod diameter $D_p$ | 1.0m |
| length $L$ | 4.3 m |
| sound absorbing material | Glass Wool 48 |
| porosity of perforated tubes | 46.2% |

Considering the parametric study results and the design constraints, the specifications of the circular-type pod silencer have been determined as design variables in Table 1. When the designed silencer is attached to the axial flow fan, the reduced noise reduction can be evaluated as follows. First, TL of the designed silencer is evaluated over the frequency range between 0 and 5 kHz as shown in Figure 12. Second the reduced noise SPL spectrum is obtained by subtracting TL from the measured noise spectrum of the axial flow fan itself as shown in Figure 12. The overall SPL of 106 dB(A) is expected to be reduced to 94 dB(A) by attaching the circular-type pod silencer.

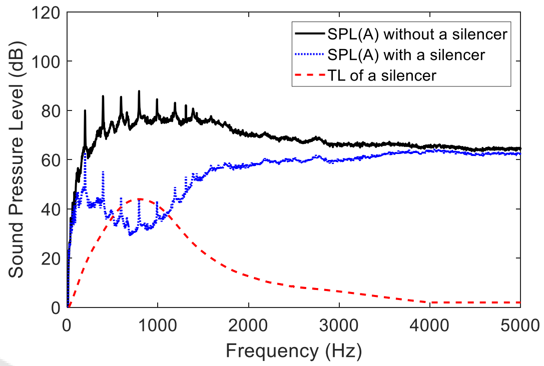


Figure 12: Reduced noise spectrum of the axial fan with the silencer, that is evaluated by subtracting TL from the measured noise spectrum of the axial fan, itself.

# 5 CONCLUSIONS

A circular-type pod silencer has been designed to reduce a high noise level that is generated from the axial flow fan in subway. In order to effectively reduce the noise, the design parametric study has been performed using FEA. It has been implemented to design the circular-type pod silencer that effectively reduces the high noise level generated from the axial flow fan. The overall SPL of 106dB(A) has been expected to be reduced to 94 dB(A). In order to get more noise reduction, a circular-type pod silencer with annular two layers can be considered. Further research is expected to design the circular-type pod silencer with annular two layers.

# ACKNOWLEDGEMENTS

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