# Design of a Perforated Muffler for a Regenerative Blower Used in Fuel Cell Application

Hyun Gwon Kil, Kwang Yeong Kim and Chan Lee
*Department of Mechanical Engineering, University of Suwon, Hwaseong-si, Gyeonggi-do, Republic of Korea*

Keywords: Perforated Muffler, Regenerative Blower, Fuel Cell Application, Transmission Loss.

Abstract: A perforated muffler has been designed to reduce a high noise level that is generated from a regenerative blower used in fuel cell applications. The noise consists of two components such as discrete high 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. Main contribution into the high noise level is due to the discrete frequency noise component at high frequency 5800 Hz. In order to effectively reduce the noise level of regenerative blowers, a perforated muffler has been modelled in this paper. In order to identify important design factors, the design parametric study has been performed using transfer matrix method and finite element method (FEM). It has been implemented to design the perforated muffler that effectively reduces the high noise level of the regenerative blower.

## 1 INTRODUCTION

Regenerative blowers are recently used in fuel cell applications because of their simple structures, easy manufacturing and operation. But those generate high noise level due to their air processing unit operating with high pressure rise at low flow capacity (Lee et al., 2013). The noise consists of two components such as discrete frequency noise component at BPF due to rotating impellers and broadband noise component due to turbulence in inflow and exhaust jet mixing. Main contribution into the high noise level is due to the discrete frequency noise component. It is needed to attach perforated mufflers to reduce the discrete frequency noise component.

The perforated mufflers have been initially analyzed by using transfer matrix method (Sullivan et al, 1978); Sullivan, 1979; Munjal, 1987). Numerical simulation methods such as boundary element method (BEM) (Wu, 1996) and finite element method (FEM) (Saf, 2010) have been also implemented for design of the perforated mufflers. Most of practical applications have been performed to reduce mainly the discrete frequency noise component in relatively low frequency region where the plane wave approximation can be valid without considering higher order modes. But the higher modes needs to be considered to design the perforated muffler attached to the regenerative blower. It is because the blower is operated at large rpm with high pressure rise and the blower noise is mainly generated at relatively high BPF. In this paper, in order to effectively reduce the noise level of regenerative blowers with BPF 5800 Hz, a perforated muffler has been modelled. In order to identify important design factors including higher modes, the design parametric study has been performed using transfer matrix method and FEM. It has been implemented to design the perforated muffler that effectively reduces the high noise level.

## 2 THEORY

### 2.1 Sound Transmission Loss

In order to reduce the noise generated at the blower, a perforated muffler in Figure 1 is attached to the blower. The noise attenuation performance of the muffler is evaluated in terms of transmission loss (TL). 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 muffler as

$$\mathrm{TL} = 10\, log_{10} \frac{W_i}{W_t} \tag{1}$$



Kil H., Kim K. and Lee C..
Design of a Perforated Muffler for a Regenerative Blower Used in Fuel Cell Application.
DOI: 10.5220/0005541104880492
In *Proceedings of the 5th International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2015), pages 488-492
ISBN: 978-989-758-120-5

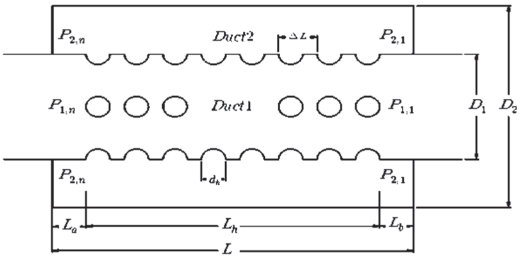


Figure 1: Perforated muffler.

## 2.2 Methods to Evaluate TL

### 2.2.1 Transfer Matrix Method

The perforated muffler is consists of parallel coupled coaxial duct. The two ducts are joined together by a perforated section of length Ls. The coaxial duct has constituent sub-components with straight parts and parts with holes, respectively. The acoustic pressure $(P_{1,n}, P_{2,n})$ and volume velocity $(U_{1,n}, U_{2,n})$ at the left end of the coaxial duct can be related with the acoustic pressure $(P_{1,1}, P_{2,1})$ and volume velocity $(U_{1,1}, U_{2,1})$ at the right ends of the coaxial duct in the matrix form as

$$\begin{bmatrix} P_{1,n} \\ U_{1,n} \\ P_{2,n} \\ U_{2,n} \end{bmatrix} = [G_n] \prod_{j=1}^{n-1} [H_j][G_j] \begin{bmatrix} P_{1,1} \\ U_{1,1} \\ P_{2,1} \\ U_{2,1} \end{bmatrix} \quad (2)$$

Here $[H_j]$ and $[G_j]$ correspond to transfer matrices of sub-components with straight parts and parts with holes, respectively. $N$ means the number of the sub-components. Considering the impedance regarding to the relation of the pressure difference and volume velocity through each hole, the pressure and volume velocity at the inlet of the muffler can be related to the pressure and volume velocity at the outlet as

$$\begin{bmatrix} P_{1,n} \\ U_{1,n} \end{bmatrix} = [T] \begin{bmatrix} P_{1,1} \\ U_{1,1} \end{bmatrix} \quad (3)$$

where $[T]$ is the overall transmission matrix. Here the impedance at each hole can be determined using the empirical formula in the reference (Sullivan, 1978)

$$Z_j = \frac{4\rho c}{\pi d_h^2} [6 \times 10^{-3} + i \times k(t + 0.75 d_h)] \quad (4)$$

where $\rho, c$, $d_h$ and $k$ are density of air, speed of sound, hole diameter and acoustic wavenumber at a given frequency, respectively. The detailed description in the formulation of the transfer matrix can be referred in the reference (Sullivan, 1979). From the relation in Equation TL can be evaluated as

$$\mathrm{TL} = 20\log\left[\frac{1}{2}|T_{11} + Z_2^{-1} T_{12} + Z_1 T_{21} + T_{22}|\right] \quad (5)$$

where $T_{ij}$ $(i, j = 1,2)$ is the corresponding element of the transfer matrix. $Z_1 (= c/S_1)$ and $Z_2$ $(= c/S_2)$ mean the characteristic impedance of two duct with section area $S_1$ and $S_2$, respectively. The transfer matrix method is generally used with the assumption of linear sound propagation of a plane wave in the muffler. The plane wave limit of a circular duct corresponds to the case below the cut-off frequency (Eriksson, 1980) with the first asymmetric mode that is

$$f_{c(1,0)} = 0.586\, c/D_2 \quad (6)$$

On the other hand, the first circularly symmetric or radial mode generated at cut-off frequency is expressed as

$$f_{c(0,1)} = 1.22\, c/D_2 \quad (7)$$

### 2.2.2 Finite Element Method

Numerical simulation methods play an increasingly important role in the design of mufflers as well as other NVH applications. FEM offers an advantageous combination of modelling flexibility, computational efficiency and result accuracy. Comparing to the boundary element method (BEM), FEM 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. FEM can be especially used to design of mufflers to reduce relatively high frequency noise considering the higher modes above the cut-off frequency as well as to design the mufflers with relatively complex shapes.

The linear wave equation for perfect gas with no damping is

$$\nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial^2 t} \quad (8)$$

At each frequency in the interested frequency range that equation (8) becomes Helmholz's equation at a as

$$\nabla^2 P = -k^2 P \quad (9)$$

where $k$means the acoustic wavenumber at the given frequency. The three dimensional acoustic domain of the muffler is divided into elements in Figure 2. The variational formulation of the muffler problem allows to formulate the discretized equation of linear systems of algebraic equations as

$$[\mathrm{A}]\{P\} = \{f\} \qquad (10)$$

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

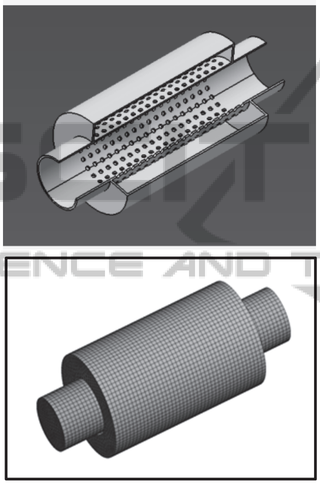

Figure 2: Structural shape and finite element model of a muffler.

In this study, the finite element method approach is done by a commercial FEM program ACTRAN of MSC software company. For more efficient way to model perforation of the muffler, 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.

# 3 ANALYSIS

## 3.1 Blower Noise Characteristics

The noise source considered in this research is a regenerative blower operating with high pressure rise at low flow capacity shown in Figure 3 (Lee et al., 2013). It is widely used in various applications

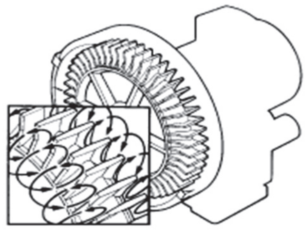

Figure 3: Regenerative blower.

The noise source considered in this research is a regenerative blower operating with high pressure rise at low flow capacity shown in Figure 3 (Lee et al., 2013). It is widely used in various applications including fuel cell applications. One of main shortcomings of the regenerative blower is high noise level. The flow inside the regenerative blower shows typically helical-toroidal motion where fluid rrotates in and passes along the space between rotating impeller blades and fixed side channels. It generates two kinds of noise components such as discrete frequency noise at BPF and the broadband noise distributed over wide frequency range which is produced due to inflow turbulence. Figure 4 shows the typical pattern of noise spectrum measured from the regenerative blower. Here BPF corresponds to 5800 Hz.

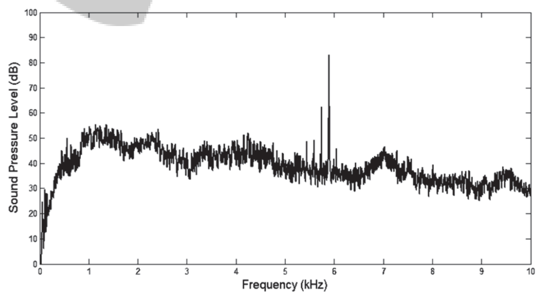


Figure 4: Noise spectrum of a regenerative blower.

## 3.2 Verification of the Methods

In order to verify the methods to evaluate TL of the muffler, the transfer matrix method and FEM have been applied to evaluate TL of the perforated muffler model in reference (Sullivan et al, 1978). The dimensions of the model are$L = 0.257m$, $D_1 = 0.508m$, $D_2 = 0.762m$. The porosity of the tube is $\sigma = 3.8\%$. The numerical results for TL have been compared with the corresponding experimental results in the reference (Sullivan et al, 1978) as shown in Figure 5. It shows that the two methods can be used to evaluate TL of the perforated muffler in good agreement with the experimental results.

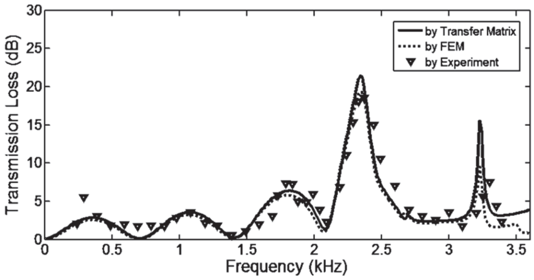


Figure 5: Comparison of the numerical results of TL of the perforated muffler by transfer matrix method and FEM with corresponding experimental results.

## 3.3 TL Characteristics of a Perforated Muffler

TL of the perforated muffler is dependent on design variables such as inner diameter $D_1$ and outer diameter $D_2$ , porosity σ, total length $L$. The inner diameter $D_1$ is determined to be fitted to the outer diameter of the blower. The outer diameter $D_2$ is determined considering the cutoff frequencies in Equations (6) and (7) although the transmission loss performance is increased by increasing the cross-sectional area ratio between the inlet and outlet ducts, The initial design length of the muffler can be determined considering the axial modal frequencies of the cavity itself as $\mathrm{f} = \mathrm{n}\ (\mathrm{c}/2\mathrm{L})$ $(n = 1,2,\cdots)$ and TL pattern of the corresponding simple expansion chamber composed of the outer duct without the inner duct. It leads to decision of the initial data for $D_1 = 0.019m, D_2 = 0.06m$ and $L = 0.083m$. The corresponding cut-off frequencies are $f_{c(1,0)} = 3320Hz$ and $f_{c(0,1)} = 6913Hz$. The dependence of TL on the porosity of the muffler is shown in Figure 6. Figure 6(a) also shows a comparison of TL result obtained by FEM with TL result obtained by the transfer matrix method with the dependence of the porosity. The comparison shows some differences between two results especially above the cut-off frequency $f_{c(1,0)} = 3320Hz$ as shown in Figure 6(c)-(e). This phenomenon is shown more clearly as the porosity is increased. It is because TL results obtained by FEM includes the contribution of all higher modes while the only plane wave is considered in the transfer matrix method. Figure 6(a) shows that a peak at an annular cavity resonator resonance is generated about at 800 Hz and clearly separated from peaks of cavity axial modal frequencies in higher frequency region. As the porosity is increased in Figures 6(b)-(e), two peaks related the annular cavity resonance and the cavity modal frequency tend to merge and strongly coupled.

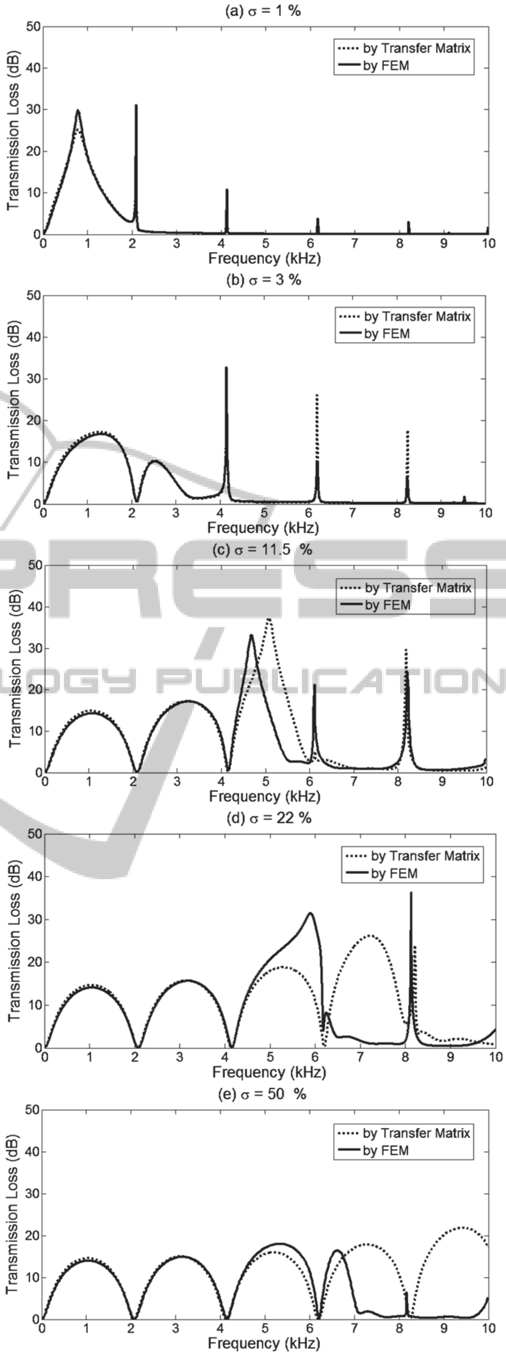


Figure 6: Transmission loss obtained by FEM $(-)$ and transfer matrix method $(\cdots)$ with dependence on the porosity.

One can find there is an optimum porosity at which two peaks merge into a single peak having relatively broad transmission loss at a particular frequency. When the optimum porosity as $\sigma = 22\%$, the corresponding single peak is generated at $5800Hz$ as shown in Figure 6(d). The peak is also found at

BPF 5800 Hz in the noise spectrum of the regenerative blower as shown in Figure 4.

# 4 RESULTS

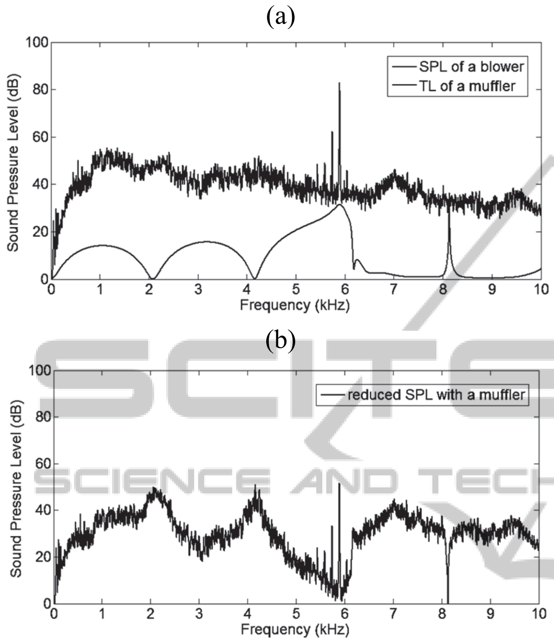


Figure 7: (a) blower noise spectrum and TL of the designed perforated muffler and (b) reduced noise spectrum.

The regenerative blower generates the noise of overall sound pressure level (SPL) 84 dB(A) with the frequency spectrum shown in Figure 7(a), that has two kinds of noise components such as discrete frequency noise at BPF 5800Hz and the broadband noise distributed over wide frequency range. In order to effectively reduce the discrete frequency noise at BPF, the perforated muffler with the porosity $\sigma = 22\%$ is designed and attached. TL of the muffler is evaluated over the frequency range between 0 and 10kHz is as shown in Figure 7(a). The overall SPL of 84 dB(A) is expected to be reduced to 72 dB(A) by attaching the perforated muffler as shown Figure 7(b) that represents the reduced noise spectrum by attaching the perforated muffler to the regenerative blower.

# 5 CONCLUSIONS

A perforated muffler has been designed to reduce a high noise level that is generated from a regenerative blower used in fuel cell applications. In order to effectively reduce discrete frequency noise component at high frequency 5800 Hz, the design parametric study has been performed using transfer matrix method and FEM. It is implemented to design the perforated muffler that effectively reduces the high noise level. The overall SPL of 84 dB has been expected to be reduced to 72 dB by attaching the perforated muffler. Further research is expected to experimentally verify the design results and to evaluate the contribution of porous material inserted inside the coaxial duct of the perforated muffler to more reduction of the blower noise.

# ACKNOWLEDGEMENTS

This work was supported by the Development of the Regenerative Blower for fuel cell application of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy.



# REFERENCES

Lee, C., Kil, H. G., Kim G.C., Kim, J. G., Ma, J. H., Chung K. H., 2013. *Aero-acoustic Performance Analysis Method of Regenerative Blower*, J*ournal. of Fluid machinery (in Korean), 16(2).*

Crocker, J. W., M. J.,1978. Analysis of concentric resonators having partitioned cavities, *Journal of Acoustical Society of America, 64(1).*

Sullivan, 1979. A method for modelling perforated muffler components. I. Theory, *Journal of Acoustical Society of America, 66(3).*

Munjal, M. L., 1987. *Acoustics of ducts and mufflers with application to exhaust and ventilation system design*, John Wiley & Sons.

Wu, T. W., Wan. G. C., 1996. Muffler performance studies using a direct mixed-body boundary element method and a three-point method for evaluating transmission loss. *ASME Transaction, Journal of Vibration and Acoustics*, 118.

Saf., O., Erol, H., 2010, On acoustics and flow behavior of the perforated mufflers, *17th International Congress on Sound & Vibration.*

Erikson, L. J., 1980. Higher order mode effects in circular ducts and expansion chambers, *Journal of Acoustical Society of America, 66(3).*

Mechel, F. P., 2008. *Formulas of Acoustics*, Springer, 2nd edition.