Development of a Perforated Diffusive Muffler for a Regenerative Blower

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Keywords: Perforated Diffusive Muffler, Regenerative Blower, Transmission Loss.

Abstract: A perforated diffusive muffler has been developed to reduce a high noise level that is generated from a regenerative blower. 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 regenerative blower. 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 regenerative blower, a perforated diffusive muffler has been designed and manufactured in this paper. Its experimental test showed that 23 dB of noise reduction has been achieved by attaching the muffler to the regenerative blower. Noise level of 85dBA generated by the regenerative blower was reduced to noise level of 62dBA.

1 INTRODUCTION

Regenerative blowers are widely used for automotive, environmental and fuel cell applications because those are usually operated with high pressure rise at low flow capacity. However, those generate high noise level due to their air processing unit operating with high pressure rise at low flow capacity (Mura and Badami, 2012). 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. 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, 1978; Sullivan, 1979; Munjal, 1987). Numerical simulation methods such as boundary element method (BEM) (Wu and Wan, 1996) and finite element method (FEM) (Saf and Erol, 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 the authors' previous paper at SIMULTECH 2015 (Kil et al., 2015) a perforated muffler has been designed in order to reduce the noise generated from a regenerative blower with BPF 5800 Hz. Recently, the research work has been extended to design of the perforated diffusive muffler by adding sound absorbing material in the perforated muffler (Jeon et al. 2017, in Korean). In the research work, the perforated diffusive muffler has been manufactured and tested experimentally. The test result showed that 23 dB of noise reduction has been achieved by attaching the muffler to the regenerative blower. Noise level of 85 dBA generated by the regenerative blower was reduced to noise level of 62 dBA. The research work is introduced in this paper in English.

2 BLOWER MODEL AND NOISE CHARACTERISTICS

2.1 Regenerative Blower Model

A regenerative blower is composed of impellers equipped on double sides of rotating plate and fixed

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side channel covering the impellers. FANDAS-Regen code (Lee et al., 2013) has been used to decide the blower's design variables and geometry are shown in Figure 1.

In order to reduce the noise generated from regenerative blower itself, a phase-shift cancellation concept (Kim et al., 2014) on impeller blade arrangement design has been implemented. Impeller blades are equipped and arranged along angular direction on double sides of rotating plate. Acoustic pressure is radiating from each impeller blade in the form of sinusoidal wave with the period of blade pitch. If the impeller blades are arranged with staggered type as shown in Figure 2, the acoustic pressure radiating from impeller on one side could be cancelled by that from impeller on another side.

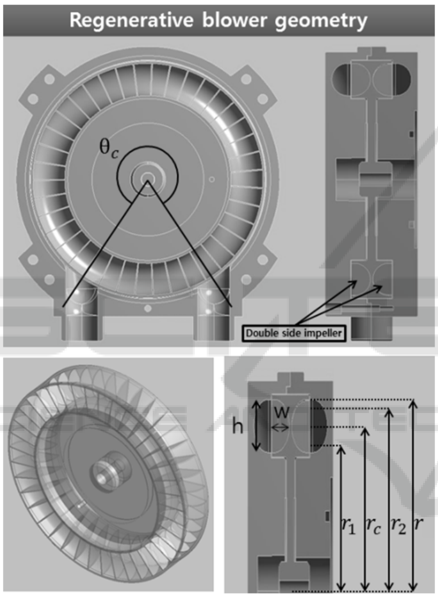


Figure 1: Geometry and design variables of regenerative blower.

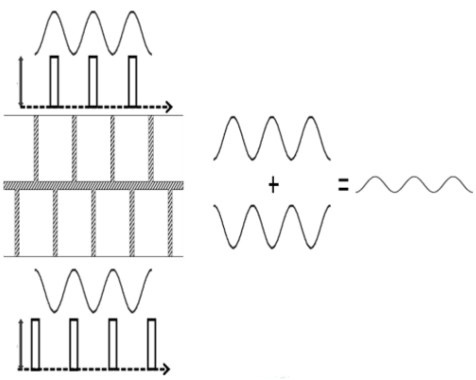


Figure 2: Phase-shift cancellation concept.

2.2 Blower Noise Characteristics

The noise source considered in this research is 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 rotates 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. The total noise level is shown as 85dB, resulting in a 22dB reduction by applying the low noise design concept in Figure 2. However, since the noise level 85dB of the regenerative blower is quite high in terms of work environment, additional noise reduction is considered to be necessary by attaching the perforated muffler.

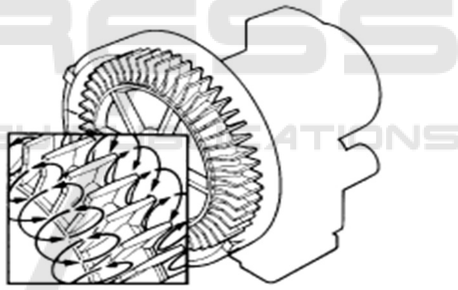


Figure 3: Regenerative blower.

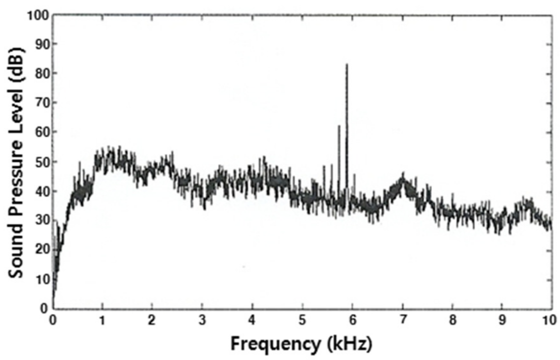


Figure 4: Noise spectrum of a regenerative blower.

3 THEORY

3.1 Sound Transmission Loss and Insertion Loss

In order to reduce the noise generated from the blower, a perforated muffler is attached to the blower. The noise attenuation performance of the muffler 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 muffler as

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

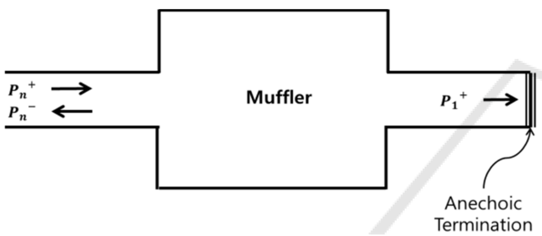


Figure 5: Layout for transmission loss.

If the area of the inlet is 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 pressuer P_1 as

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

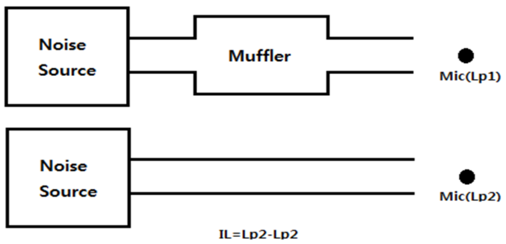


Figure 6: Layout for insertion loss.

IL is defined as the difference between sound power level Lp_2 at the termination without the muffler and sound power level Lp_1 at the termination with the muffler installed as shown in Figure 6. In the case of IL, it is not necessary to install an anti-reflection terminal as shown in Figure 5. Thus it is closer to an actual value of sound loss because all actually installed connectors related to the blower and the muffler 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 muffler in this paper.

3.2 Methods to Evaluate TL

3.2.1 Transfer Matrix Method

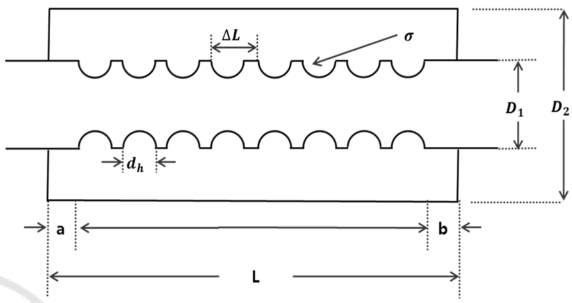


Figure 7: Perforated muffler.

The perforated muffler is consists of parallel coupled coaxial duct as shown in Figure 7. The two ducts are joined together by a perforated section. 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 inlet 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 outlet ends of the coaxial duct in the matrix form (Sullivan, 1978; Sullivan, 1979; Bang, 2001) as

$$\begin{bmatrix} P_{1,n} \\ U_{1,n} \\ P_{2,n} \\ U_{2,n} \end{bmatrix} = [G_n] \prod_{j=1}^{n-1} [H_j][G_j] \begin{bmatrix} P_{1,1} \\ U_{1,1} \\ P_{2,1} \\ U_{2,1} \end{bmatrix} \tag{3}$$

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

$$\begin{bmatrix} P_{1,n} \\ U_{1,n} \end{bmatrix} = [T] \begin{bmatrix} P_{1,1} \\ U_{1,1} \end{bmatrix} \tag{4}$$

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)

$$Z_j = \frac{4\rho c}{\pi d_h^2}[6 \times 10^{-3} + i \times k(t + 0.75 d_h)] \quad (5)$$

where ρ, 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: Bang 2001). From the relation in Equation (4), TL can be evaluated as

$$\mathrm{TL} = 20\log\left[\frac{1}{2}|T_{11} + Z_2^{-1}T_{12} + Z_1 T_{21} + T_{22}|\right] \quad (6)$$

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

$$f_{c(1,0)} = 0.586\, c/D_2 \quad (7)$$

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

$$f_{c(0,1)} = 1.22\, c/D_2 \quad (8)$$

3.2.2 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.

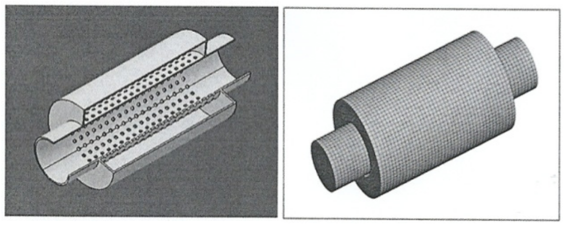


Figure 8: Structural shape and finite element model of a muffler.

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

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial^2 t} \quad (9)$$

At each frequency in the interested frequency range that Equation (9) becomes Helmholz's equation as

$$\nabla^2 P = -k^2 P \quad (10)$$

where P, k mean complex pressure amplitude and the acoustic wavenumber at the given frequency, respectively. The three dimensional acoustic domain of the muffler is divided into elements in Figure 8. The variational formulation of the muffler problem allows to formulate the discretized equation of linear systems of algebraic equations as

$$[\mathrm{A}]\{P\} = \{f\} \quad (11)$$

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 muffler problem, {f} is only a non-zero value at the inlet pipe according to Dirichlet boundary condition with unit pressure.

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.

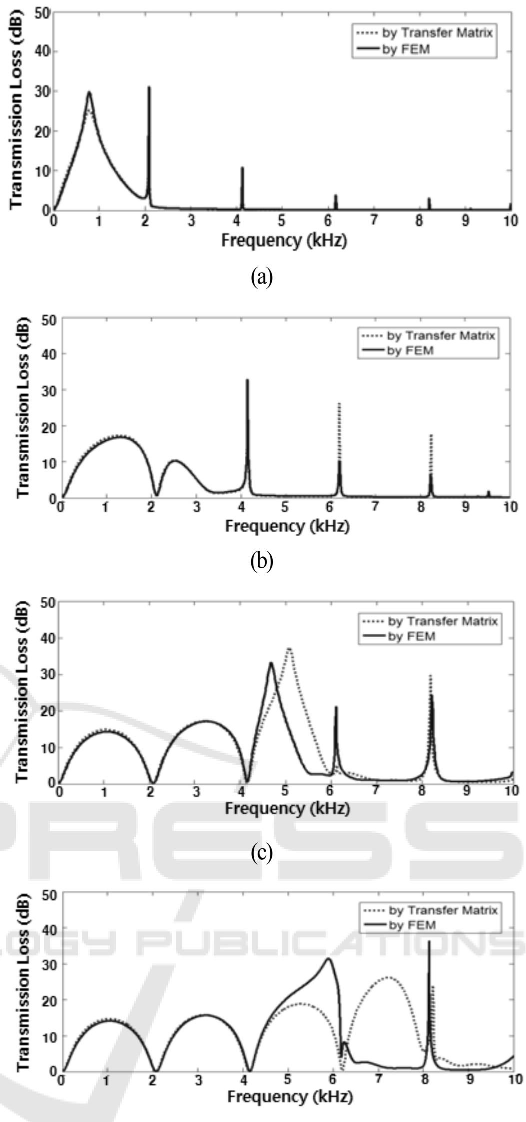
4 DESIGN

4.1 Design Concepts

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 in Figure 7. 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 cut-off frequencies in Equations (7) and (8) although TL performance is increased by increasing the cross-sectional area ratio between the inlet and outlet ducts at frequencies below the corresponding cut-off frequency. The initial design length of the muffler can be determined considering the axial modal frequencies of the cavity itself as $f = n\ (c/2L)\ (n = 1,2,\cdots)$. It leads to decision of the initial data as $D_1 = 0.019m$, $D_2 = 0.06m$ and $L = 0.083m$. The corresponding cut-off frequencies are $f_{c(1,0)} = 3320Hz$ and $f_{c(0,1)} = 6913Hz$.

Figure 9 shows the dependence of TL on the porosity of the muffler and also 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 9(c) and (d). 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.

Characteristics of the perforated muffler are represented by the combination of the acoustic mode of the outer tube and the effect of the resonance due to porosity of holes in the inner perforated tube. Those phenomena can be considered in designing the perforated muffler. Figure 9(a) shows that at low porosity a peak at an annular cavity resonator resonance related to the porosity is clearly separated from peaks of cavity axial modal frequencies in higher frequency region. As the porosity is increased in Figures 9(b)-(d), two peaks related the annular cavity resonance related to the porosity and the cavity modal frequency tend to merge and to be strongly coupled. One can find an optimum porosity at which two peaks merge into a single peak having relatively broad transmission loss at a particular frequency band that includes BPF in the nose spectrum generated by the blower.

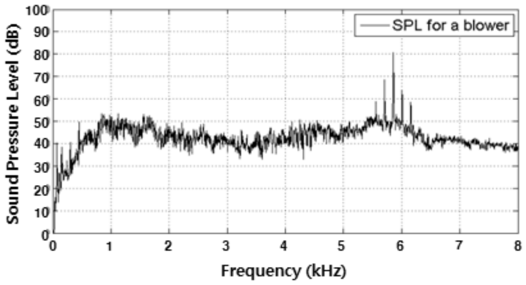


(a) (b) (c) (d)

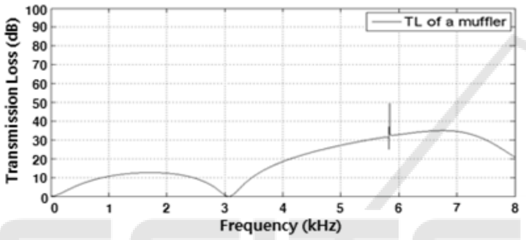
Figure 9: Transmission loss obtained by FEM $(-)$ and transfer matrix method $(\cdots)$ with dependence on the porosity (σ) : (a) 1%, (b) 3%, (c) 11.5%, (d) 22%.

4.2 Design and Evaluation of Noise Reduction Performance

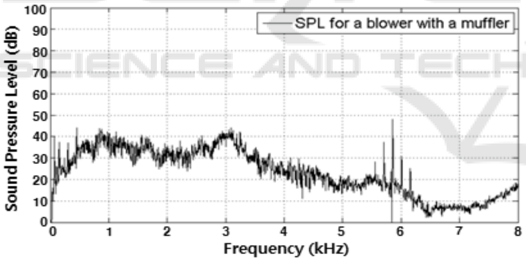
The design concept described at section 4.1 has been implemented to design of a perforated muffler. The inner diameter of the muffler has been determined to be fitted to the outer diameter of the blower as $D_1 = 0.019$. The outer diameter has been determined to be $D_2 = 0.052m$ to increase the cut-off frequency as $f_{c(0,1)} = 8000Hz$ comparing with the initial cut-off frequency $f_{c(0,1)} = 6913Hz$. The length of the muffler has been determined as L=59mm to expand frequency bandwidth for noise reduction comparing with the initial length $L = 0.083m$. The porosity of the holes has been determined to be $\sigma = 36\%$ to reduce discrete frequency noise at BPF. The noise reduction characteristics of the muffler with those specifications are shown in Figure 10 is analyzed as follows.



(a)



(b)



(c)

Figure 10: (a) blower noise spectrum, (b) TL of the designed perforated muffler and (c) 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 10(a), that has two kinds of noise components such as discrete frequency noise at BPF 5,800Hz and the broadband noise distributed over wide frequency range. By attaching the perforated muffler with TL in Figure 10(b), the overall SPL of 84 dB(A) is expected to be reduced to 66 dB(A) in Figure 10(c) that represents the reduced noise spectrum by attaching the perforated muffler to the regenerative blower.

5 EXPERIMENT AND RESULTS

5.1 Performance of the Perforated Muffler

The perforated muffler has been manufactured. It has a relatively small size with length less than the length of a credit card as shown in Figure 11. TL of the manufactured perforated muffler has been measured by comparing noise levels with and without the muffler with the layout of the IL as shown in Figure 6. It matches relatively well the estimated value of TL as shown in Figure 12.

Figure 11: Perforated muffler.

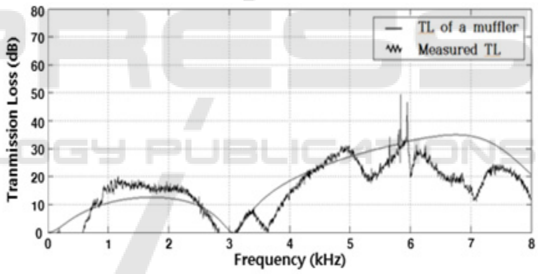
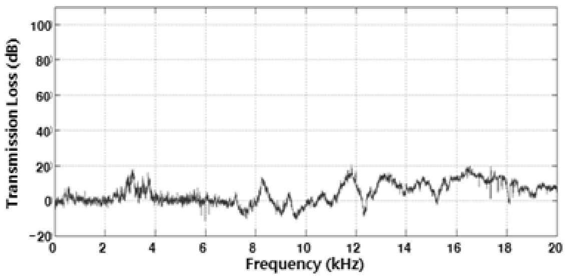


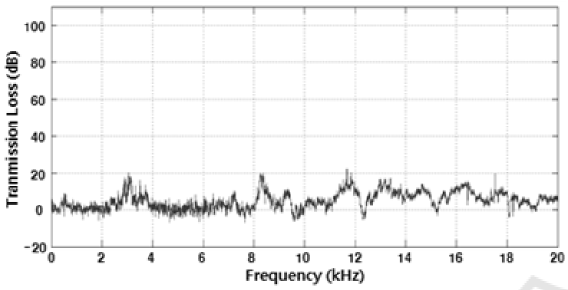
Figure 12: TL of a perforated muffler.

5.2 Effects of Sound Absorbing Material

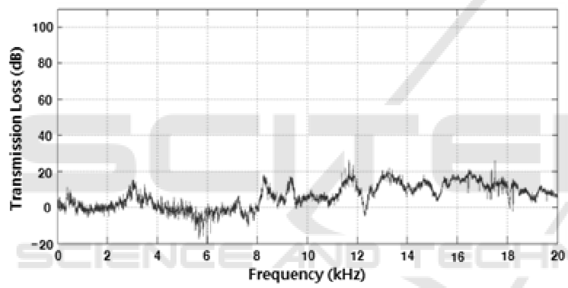
Fig. 12 shows low value of TL at 3 kHz. In order to increase the noise absorption performance around 3 kHz, three sound absorbing materials such as PU foam 32k, Melamine foam G, and Websuler 300G (*NYCO*, 2010) are selected to insert each of those between the coaxial ducts of the muffler. Three perforated diffusive mufflers with those sound absorbing materials, respectively, were manufactured. TL of each perforated diffusive muffler has been measured and noise absorbing performance of each material itself was separated as shown in Figure 13. It shows that those materials have all noise absorption effects at 3kHz and frequencies above 8 kHz.



(a)



(b)



(c)

Figure 13. Noise absorbing performance (a) PU foam 32k, (b) Melamine foam G and (c) Websuler 300G.

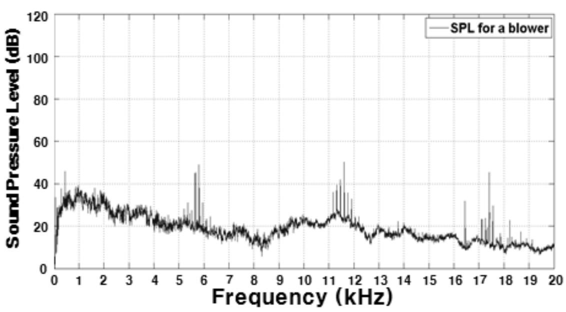


Figure 14: Noise spectrum of regenerative blower with attached perforated diffusive muffler.

5.3 Performance of the Perforated Diffusive Muffler

Each muffler was attached to the regenerative blower and noise was measured. The overall noise levels were 65dB, 62dB and 70dB, respectively. Figure 14 shows the noise (62 dB) characteristics of a blower that is attached to the perforated diffusive muffler with noise absorbing material as Melamine form G.

6 CONCLUSIONS

A perforated diffusive muffler has been designed and manufactured to reduce a high noise level that is generated from a regenerative blower. 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 blower. Main contribution into the high noise level is due to the discrete frequency noise component. 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. Effects of noise absorbing materials have been investigated experimentally. By combining effects of a perforated muffler and noise absorbing material, a perforated diffusive muffler has been designed and manufactured. Its experimental test showed that 23 dB of noise reduction has been achieved by attaching the muffler to the regenerative blower. Noise level of 85dBA generated by the regenerative blower was reduced to noise level of 62dBA.

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