# Analysis of Higher Order Mode Wave in Air Ventilation Grille

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A conceptual model for manufacturing the new type of soundproofing ventilation grille unit is present. The central problem is designing the shape and dimension of this unit and the placement of these input and output opening in such a way as to maximize ventilation as well as preventing outside noise from entering the home. In this work, a method to predict the insertion-loss of ventilation grille unit is proposed by solving the wave equation, considering the resonance frequencies of higher-order mode.
**Keywords:** Noise, higher-order mode, insertion loss

## 1. INTRODUCTION

Numerous studies on assessing the acoustic performance of vented facades to inner rooms have been published. However, there are still limited researches on the particular case of housing in tropical and developing country where the noise propagation needs to be prevented and the natural ventilation is demanded. As shown in **Fig.1**, ventilation grille consisted of several slits opening side by side in a wall is widely used in tropical climates countries.

However, the annual increase in traffic noise in developing tropical countries has rendered this kind of ventilation grille to be useless because it serve a direct pathway for traffic noise to enter the home. In this report we deal with a ventilation grille consisted of several slits opening side by side in a wall. A method to predict the sound propagation in ventilation grille unit is proposed by solving the wave equation, considering the resonance frequencies of higher-order mode.

## 2. METHOD OF ANALYSIS

Model of the ventilation grille is shown in **Fig.2**. A section area $S_w = a \times b$ and depth $L$ of rectangular cavity that has $N$ inputs and $M$ outputs at both side. Here, we present the theoretical calculation of the sound pressure inside the ventilation grille including the effects of higher-order mode wave for a simple case where no acoustic material is used.

Wave equation in term of the velocity potential is given by

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)\Phi = \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\Phi \tag{1}$$

where $c$ is sound velocity, Let $\Phi = \sqrt{2}\,\phi \exp(j\omega t)$ ( $j^2=-1$, $\omega = kc$, $k$ : wave number) then the complete solution of Eq.(1) is given by

$$\phi = \left( Ae^{\mu z} + Be^{-\mu z} \right)\left( C\sin\alpha x + D\cos\alpha x \right)$$
$$\left( E\sin\sqrt{s^2-\alpha^2}\,y + F\cos\sqrt{s^2-\alpha^2}\,y \right) \tag{2}$$

where $A$, $B$, $C$, $D$, $E$ and $F$ are arbitrary constants determinable from the boundary conditions, $\alpha$, $s$ and $\mu$ are the constants.

Let $V_x = -\partial\phi / \partial x$, $V_y = -\partial\phi / \partial y$ and $V_z = -\partial\phi / \partial z$ be the velocity components in the $x$, $y$ and $z$ directions, respectively. At the left and the right side of the ventilation grill as shows in **Fig. 1**, the boundary conditions are

$$[1] \quad V_x = 0 \text{ at } x = 0 \tag{3}$$

$$[2] \quad V_x = 0 \text{ at } x = a \tag{4}$$

$$[3] \quad V_y = 0 \text{ at } y = 0 \tag{5}$$

$$[4] \quad V_y = 0 \text{ at } y = b \tag{6}$$

At the front side of ventilation grille, the velocity component in z direction be the sum of $N$ inputs which has a velocity $V_0^{(i)}$ $(i = 1, ..., N)$, respectively.

[5] at $z = 0$

$$V_z = V_0^{(1)} F_0^{(1)}(x, y) + V_0^{(2)} F_0^{(2)}(x, y) + \cdots$$
$$+ V_0^{(N)} F_0^{(N)}(x, y) = \sum_{i=1}^{N} V_0^{(i)} F_0^{(i)}(x, y) \tag{7}$$

where $F_0^{(i)}(x, y) = 1$ at the input section area and $F_0^{(i)}(x, y) = 0$ elsewhere.

Similarly, At the back side of ventilation grille, the velocity component in z direction be the sum of $M$ output which has a velocity $V_L^{(i)}$ $(i = 1, ...., M)$, respectively.

[6] at $z = L$

$$V_z = V_L^{(1)} F_L^{(1)}(x, y) + V_L^{(2)} F_L^{(2)}(x, y) + \cdots$$
$$+ V_L^{(M)} F_L^{(N)}(x, y) = \sum_{i=1}^{M} V_L^{(i)} F_L^{(i)}(x, y) \tag{8}$$

where $F_L^{(i)}(x, y) = 1$ at the output section area and $F_L^{(i)}(x, y) = 0$ elsewhere.

According to the boundary conditions Eq.(3)-(6), $\phi$ can be determined [ see Appendix]. By using the relation $P_L = jk\rho c\phi(x, y, L)$, the sound pressure at the outside can be obtained. The average of sound pressure at the outside becomes.

$$\bar{P}_L = j\frac{4k\rho c}{S_w}\left[\frac{1}{\sin(kL)}\left(-\sum_{i=1}^{N} U_0^{(i)} + \cos(kL)\sum_{i=1}^{M} U_L^{(i)}\right) + \sum\left\{\frac{1}{\mu_{m,n}\sinh(\mu_{m,n}L)}\theta_{m,n}\,\Delta_{m,n} + \frac{\cosh(\mu_{m,n}L)}{\mu_{m,n}\sinh(\mu_{m,n}L)}\lambda_{m,n}\,\Delta_{m,n}\right\}\right] \tag{9}$$

where

$$\theta_{m,n} = \sum_{i=1}^{N} \int_{a_{00}^{(i)}}^{a_{01}^{(i)}} \int_{b_{00}^{(i)}}^{b_{01}^{(i)}} \frac{U_0^{(i)}}{S_0^{(i)}} \cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right) dx\,dy \tag{10}$$

$$\lambda_{m,n} = \sum_{i=1}^{M} \int_{a_{L0}^{(i)}}^{a_{L1}^{(i)}} \int_{b_{L0}^{(i)}}^{b_{L1}^{(i)}} \frac{U_L^{(i)}}{S_L^{(i)}} \cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right) dx\,dy \tag{11}$$

$$\Delta_{m,n} = \sum_{i=1}^{M} \frac{1}{S_L^{(i)}} \int_{a_{L0}^{(i)}}^{a_{L1}^{(i)}} \int_{b_{L0}^{(i)}}^{b_{L1}^{(i)}}$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)dx\,dy \quad (12)$$

$$\mu_{m,n} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 - k^2} \qquad (13)$$

the symbol $\dot{\underset{\bullet}{\sum}}$ means $\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}$ without $m$=$n$=0. The first term on the bracket represents the sound pressure of the plane wave and the second one represents the sound pressure components of the higher-order mode wave, respectively. From Eq.(9) $\overline{P}_L$ become great when at the following resonance frequencies of

$$\sin(kL) = 0 \quad \therefore \quad f = \eta\frac{c}{2L} \quad (\eta = 1, 2, 3....) \; (14)$$

$$\mu_{m,n}\sinh\left(\mu_{m,n}L\right) = 0$$

$$\therefore f_{m,n} = \frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 - \left(\frac{\eta\pi}{L}\right)^2}$$

$$(\eta = 0, 1, 2...) \quad (15)$$

Generation mechanism of these frequencies can be understood according to Eq.(14) and Eq.(15). The former and the latter also have many resonance frequencies occurred corresponding to the increasing of $\eta$. Therefore, it is clear that when we can eliminate an arbitrary higher-order mode wave mode by any method, we will not only avoid many resonances generated by this mode but also obtain the low level of the entire output sound pressure. In order to have a great soundproffing capability, it is necessary to minimize those level of higher-order mode wave defined by $\Delta_{m,n}$, $\lambda_{m,n}$ and $\theta_{m,n}$ in Eq.(10)-Eq.(12) at least. When we select the integration interval from 0 to *a*, not only all of odd mode waves but also many even mode waves can be eliminate. To examine the accuracy of our calculation result, the insertion loss measurement was carried out. The measurement method is based on Ref [1] with an example when ventilation grille having one input and one output as shown in **Fig.3** and the result is shown in **Fig.4**. Dimension of ventilation grille is 48cm x 7.5cm x 29cm and all of input and output have a same cross section area of 86.4cm$^2$. All odd and some even higher order mode can be eliminated when changing the interval of integration in $\Delta_{m,n}$.

## 3. CONCLUSIONS

A method to predict the sound propagation in ventilation grille unit is proposed by solving the wave equation, considering the resonance frequencies of higher-order mode. In order to maximize the soundproofing capability, it is necessary to decide the position of each input and output defined by Eq.(11)-Eq.(13). This technology will be present in an upcoming report.

## 4. APPENDIX

In order to find $\phi$ from Eqs.(3) to (8), let $\phi_a$ be the solution of Eq.(2) obtained for the following boundary conditions:

[1] at $x = 0$, $-\partial\phi_a/\partial x = 0$ (A-1)

[2] at $x=a$, $-\partial\phi_a/\partial x=0$ (A-2)

[3] at $y=0$, $-\partial\phi_a/\partial y=0$ (A-3)

[4] at $y=b$, $-\partial\phi_a/\partial y=0$ (A-4)

[5] at $z=0$,

$$-\partial\phi_a/\partial z=\sum_{i=1}^{M}V_0^{(i)}F_0^{(i)}(x,y) \quad \text{(A-5)}$$

[6] at $z=L$, $-\partial\phi_a/\partial z=0$ (A-6)

and let $\phi_b$ be the solution of Eq.(2) obtained for the following boundary conditions:

[1] at $x=0$, $-\partial\phi_b/\partial x=0$ (A-7)

[2] at $x=a$, $-\partial\phi_b/\partial x=0$ (A-8)

[3] at $y=0$, $-\partial\phi_b/\partial y=0$ (A-9)

[4] at $y=b$, $-\partial\phi_b/\partial y=0$ (A-10)

[5] at $z=0$, $-\partial\phi_b/\partial z=0$ (A-11)

[6] at $z=L$,

$$-\partial\phi_b/\partial z=\sum_{i=1}^{M}V_L^{(i)}F_L^{(i)}(x,y) \quad \text{(A-12)}$$

then $\phi$ can be obtained as $\phi=\phi_a+\phi_b$.

At first, $\phi_a$ can be derive as following procedure. From (A-1) we have

$$\frac{\partial}{\partial x}\left(C\sin\alpha x+D\cos\alpha x\right)\Big|_{x=0}=0$$

$$\therefore \quad C=0 \quad \text{(A-13)}$$

From(A-2)

$$\frac{\partial}{\partial x}D\cos\alpha x\Big|_{x=a}=0$$

$$\therefore \quad \alpha=m\frac{\pi}{a} \quad (m=0,1,2,\cdots,L) \quad \text{(A-14)}$$

Substituting Eqs.(A-13)-(A-14)into Eq. (2)

$$\phi=\sum_{m=0}^{\infty}\left(Ae^{\mu z}+Be^{-\mu z}\right)\cos\left(m\frac{\pi}{a}\right)$$

$$\left(E\sin\sqrt{s^2-\alpha^2}\,y+F\cos\sqrt{s^2-\alpha^2}\,y\right) \quad \text{(A-15)}$$

from Eq. (A-3)

$$\frac{\partial}{\partial y}\left(E\sin\sqrt{s^2-\alpha^2}\,y+F\cos\sqrt{s^2-\alpha^2}\,y\right)\Big|_{y=0}=0$$

$$\therefore \quad E=0 \quad \text{(A-16)}$$

and from Eq. (A-4)

$$\frac{\partial}{\partial y}\left(F\cos\sqrt{s^2-\alpha^2}\,y\right)\Big|_{y=b}=0$$

$$\therefore \sqrt{s^2-\alpha^2}=n\frac{\pi}{b}\left(n=0,1,\cdots,L\right) \quad \text{(A-17)}$$

Substituting (A.16) and (A.17) into Eq. (A-15), we have

$$\phi_a=\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\left(Ae^{\mu_{m,n}z}+Be^{-\mu_{m,n}z}\right)$$

$$\cos\left(\frac{m\pi y}{a}\right)\cos\left(\frac{n\pi y}{b}\right) \quad \text{(A-18)}$$

where

$$\mu_{m,n}=\sqrt{\left(m\pi/a\right)^2+\left(n\pi/b\right)^2-k^2} \quad \text{(A-19)}$$

from Eq. (A-6)

$$\frac{\partial}{\partial z}\left(Ae^{\mu_{m,n}z}+Be^{-\mu_{m,n}z}\right)\Big|_{z=L}=0$$

$$\therefore \quad B=Ae^{2\mu_{m,n}L} \quad \text{(A-20)}$$

Substituting into Eq. (A-18)

$$\phi_a=\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}e^{\mu_{m,n}L}\cosh\left(\mu_{m,n}(z-L)\right)C_{m,n}^{a}$$

$$\cos\left(\frac{m\pi y}{a}\right)\cos\left(\frac{n\pi y}{b}\right) \qquad \text{(A-21)}$$

from Eq. (A-5)

$$-\frac{\partial}{\partial z}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty} e^{\mu_{m,n}L}\cosh\left(\mu_{m,n}(z-L)\right)C_{m,n}^{a}$$

$$\cos\left(\frac{m\pi y}{a}\right)\cos\left(\frac{n\pi y}{b}\right)\Bigg|_{z=0}$$

$$=\sum_{i=1}^{N} V_0^{(i)}F_0^{(i)}(x,y) \qquad \text{(A-22)}$$

By multiplying both sides of Eq.(A-22) by $\cos(m\pi x/a)\cos(n\pi y/b)$ and integrating with respect to *x* from 0 to *a* and with respect to *y* from 0 to *b* we can determine the constant $C_{m,n}^{a}$.

$$\sum_{m=0}^{\infty}\sum_{n=0}^{\infty} e^{\mu_{m,n}L}\sinh\left(\mu_{m,n}L\right)C_{m,n}^{a}$$

$$\int_0^a\int_0^b \cos\left(\frac{m\pi x}{a}\right)^2\cos\left(\frac{n\pi y}{b}\right)^2 dx\,dy$$

$$=\sum_{i=1}^{N}\int_0^a\int_0^b V_0^{(i)}F_0^{(i)}(x,y)$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)dx\,dy$$

$$\sum_{m=0}^{\infty}\sum_{n=0}^{\infty} e^{\mu_{m,n}L}\sinh\left(\mu_{m,n}L\right)C_{m,n}^{a}\left(\frac{ab}{4}\right)$$

$$=\sum_{i=1}^{N}\int_0^a\int_0^b V_0^{(i)}F_0^{(i)}(x,y)$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)dx\,dy \qquad \text{(A-23)}$$

let $\theta_{m,n}$ is the right term of Eq.(A-23)

$$\theta_{m,n}=\sum_{i=1}^{N}\int_0^a\int_0^b V_0^{(i)}F_0^{(i)}(x,y)$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)dx\,dy$$

$$=\sum_{i=1}^{N}\int_{a_{00}^{(i)}}^{a_{01}^{(i)}}\int_{b_{00}^{(i)}}^{b_{01}^{(i)}} V_0^{(i)}$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)dx\,dy$$

$$=\sum_{i=1}^{N}\int_{a_{00}^{(i)}}^{a_{01}^{(i)}}\int_{b_{00}^{(i)}}^{b_{01}^{(i)}} \frac{U_0^{(i)}}{S_0^{(i)}}$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)dx\,dy \qquad \text{(A-24)}$$

where $U_0^{(i)}$ is the volume velocity at the output defined by $U_0^{(i)}=V_0^{(i)}S_0^{(i)}$.

Next, find $C_{m,n}^{a}$ from (A-23) and substituting to (A-21), then $\phi_a$ is obtained as

$$\phi_a=\frac{4}{S_w}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{\cosh\left(\mu_{m,n}(z-L)\right)}{\mu_{m,n}\sinh\left(\mu_{m,n}L\right)}\theta_{m,n}$$

$$\cos\left(\frac{m\pi y}{a}\right)\cos\left(\frac{n\pi y}{b}\right) \qquad \text{(A-25)}$$

Similarly, by using Eqs. (A-7) - (A.12), $\phi_b$ can be obtained as

$$\phi_b=\frac{4}{S_w}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{\cosh\left(\mu_{m,n}z\right)}{\mu_{m,n}\sinh\left(\mu_{m,n}L\right)}\lambda_{m,n}$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right) \qquad \text{(A-26)}$$

where

$$\lambda_{m,n} = \sum_{i=1}^{M} \int_{a_{L0}^{(i)}}^{a_{L1}^{(i)}} \int_{b_{L0}^{(i)}}^{b_{L1}^{(i)}} \frac{U_L^{(i)}}{S_L^{(i)}}$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right) dx\, dy \quad \text{(A-27)}$$

as mentioned above, $\phi$ is the sum of $\phi_a$ and $\phi_b$, then we obtain

$$\phi(x,y,z) = \phi_a + \phi_b$$

$$= \frac{4}{S_w}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\left\{\frac{\cosh(\mu_{m,n}(z-L))}{\mu_{m,n}\sinh(\mu_{m,n}L)}\theta_{m,n} + \frac{\cosh(\mu_{m,n}z)}{\mu_{m,n}\sinh(\mu_{m,n}L)}\lambda_{m,n}\right\}$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right) \quad \text{(A-28)}$$

The sound pressure at the input is given by

$P_0 = jk\rho c\phi(x,y,0)$ becomes

$$P_0 = j\frac{4k\rho c}{S_w}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}$$

$$\left\{\frac{\cosh(-\mu_{m,n}L)}{\mu_{m,n}\sinh(\mu_{m,n}L)}\theta_{m,n} + \frac{1}{\mu_{m,n}\sinh(\mu_{m,n}L)}\lambda_{m,n}\right\}$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right) \quad \text{(A-29)}$$

The sound pressure at the output is given by

$P_L = jk\rho c\phi(x,y,L)$

$$P_L = j\frac{4k\rho c}{S_w}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}$$

$$\left\{\frac{1}{\mu_{m,n}\sinh(\mu_{m,n}L)}\theta_{m,n} + \frac{\cosh(\mu_{m,n}L)}{\mu_{m,n}\sinh(\mu_{m,n}L)}\lambda_{m,n}\right\}$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right) \quad \text{(A-30)}$$

Therefore, average sound pressure at the output piston becomes

$$\overline{P}_L = \sum_{i=1}^{M}\frac{1}{S_L^{(i)}}\int_{a_{L0}^{(i)}}^{a_{L1}^{(i)}}\int_{b_{L0}^{(i)}}^{b_{L1}^{(i)}} P_L\, dx\, dy$$

$$= j\frac{4k\rho c}{S_w}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\left\{\frac{1}{\mu_{m,n}\sinh(\mu_{m,n}L)}\theta_{m,n}\right.$$

$$\left. + \frac{\cosh(\mu_{m,n}L)}{\mu_{m,n}\sinh(\mu_{m,n}L)}\lambda_{m,n}\right\}\Delta_{m,n} \quad \text{(A-31)}$$

where

$$\Delta_{m,n} = \sum_{i=1}^{M}\frac{1}{S_L^{(i)}}\int_{a_{L0}^{(i)}}^{a_{L1}^{(i)}}\int_{b_{L0}^{(i)}}^{b_{L1}^{(i)}}$$

$$\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right) dx\, dy \quad \text{(A-32)}$$

Expanding (A-31) with $m$=0 and $n$=0, average sound pressure at the output becomes

$$\overline{P}_L = j\frac{4k\rho c}{S_w}\left[\frac{1}{\sin(kL)}\right.$$

$$\left(-\sum_{i=1}^{N}U_0^{(i)} + \cos(kL)\sum_{i=1}^{M}U_L^{(i)}\right)$$

$$+\dot{\sum}\left\{\frac{1}{\mu_{m,n}\sinh(\mu_{m,n}L)}\theta_{m,n}\Delta_{m,n}\right.$$

$$\left.\left. + \frac{\cosh(\mu_{m,n}L)}{\mu_{m,n}\sinh(\mu_{m,n}L)}\lambda_{m,n}\Delta_{m,n}\right\}\right] \quad \text{(A-33)}$$

where the symbol $\dot{\sum}$ means $\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}$ without $m$=$n$=0.

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**Figure1.** Ventilation grille used in tropical climates countries

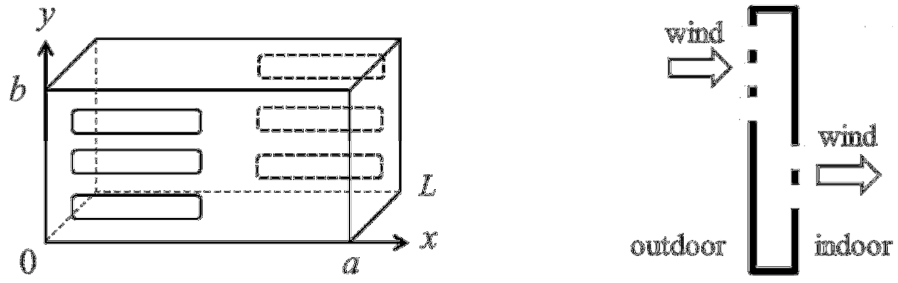
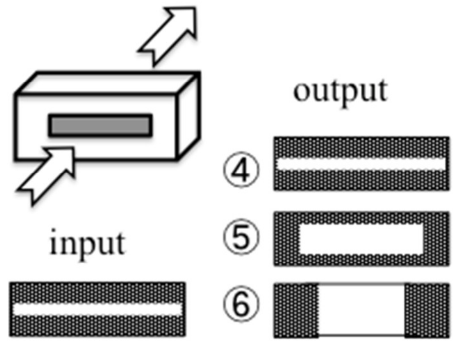



**Figure2.** Model of ventilation grille



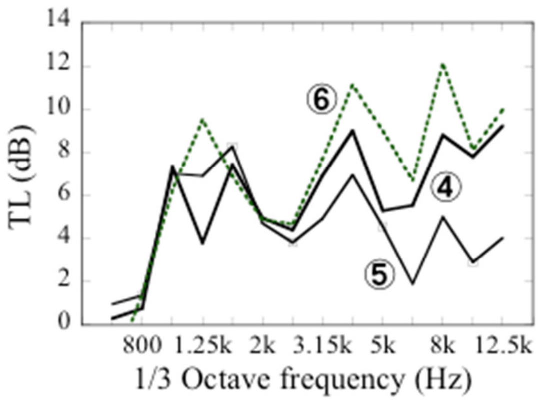




**Figure3.** Experimental with ventilation grille having one input and one output.

**Figure4.** Insertion loss measurement result