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Acoustic performance of soundproof ventilation units installed in dwelling walls

Sohei NISHIMURA[1]; Yuya NISHIMURA[1]; Thu Lan NGUYEN[2]

[1] National Institute of Technology Kumamoto College, Japan

[2] Shimane University, Japan.

ABSTRACT

This paper describes the design of the soundproof ventilation unit for installation inside the wall of a house. For this purpose, the rectangular cube or elliptic cylinder form is reasonable as the unit shape. In this paper, at first, the theoretical calculations of the sound pressure inside the rectangular cube and elliptic cylinder are carried out by solving the wave equation. Next, the resonance frequencies of the higher-order mode wave component are calculated for a rectangular cube and elliptic cylinder of the same volume. In order to have more soundproofing efficient, the comparison of resonance frequencies of the higher-order mode wave between the rectangular cube and elliptic cylinder is also discussed.

Keywords: Higher-order mode, Resonance, Sound propagation

1. INTRODUCTION

A large number of houses in developing Asia countries are being affected by road traffic noise emission from motorcycles which create frequent klaxon sounds by reported (1,2,3). On the other hand, the use of ventilation holes for providing healthy indoor air is commonly found in those countries. However, these ventilation holes also provide direct paths for traffic noise to enter a residence by reported (4). This paper describes the design of the soundproof ventilation unit for installation inside the wall of a house as shown in Fig.1. For this purpose, the rectangular cube or elliptic cylinder form is reasonable as the unit shape. The sound pressure propagating in the unit has a standing wave and higher-order mode wave components. The latter occurs in the high-frequency range. The noise tends to increase in this frequency range due to higher order mode resonance. In this paper, at first, the theoretical calculations of the sound pressure inside the rectangular cube and elliptic cylinder are carried out by solving the wave equation. Next, the resonance frequencies of the higher-order mode wave component are calculated for a rectangular cube or elliptic cylinder of the same volume. In order to have more soundproofing efficient, the comparison of resonance frequencies of the higher-order mode wave between the rectangular cube and elliptic cylinder is also discussed.

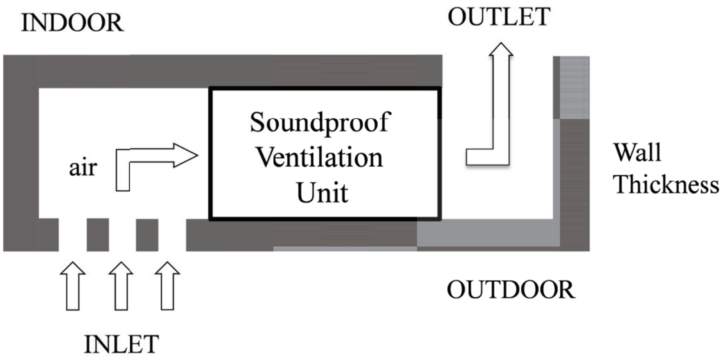

Figure 1 – Soundproof Ventilation Unit

[1] nisimura@kumamoto-nct.ac.jp
[1] nishimura@kumamoto-nct.ac.jp
[2] lan@riko.shimane-u.ac.jp

2. METHOD OF ANALYSIS

2.1 Rectangular Cube

The model of analysis is shown in Fig. 2. A cross-section area $S_w = a \times b$ and length L of rectangular cube that has an input and output at both side, the cross-sectional area of them are $S_0 = a_0 \times b_0$ and $S_L = a_L \times b_L$, respectively.

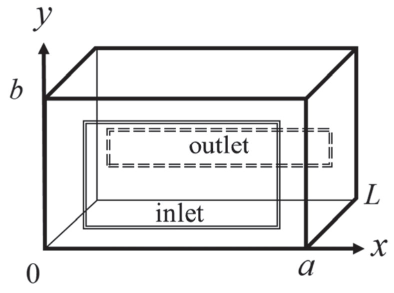

Figure 2 Model of analysis

Wave equation in terms of velocity potential Φ 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 the sound velocity. Let $\Phi = \sqrt{2}\,\phi \exp(j\omega t)$ ($j^2 = -1$, $\omega = kc$, k :wave number) then the general solution of Eq.(1) can be given as

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

Here, j^2 = -1, A, B, C, D, E and F are arbitrary constants determinable from the boundary conditions, other symbols are constants.

Let $V_x = -\partial\phi / \partial x$, $V_y = -\partial\phi / \partial y$ and $V_z = -\partial\phi / \partial z$ are the velocity component in the x, y and z directions, respectively. We assume the walls of the cavity to be perfectly rigid therefore the boundary conditions may be expressed as

[1] at $x = 0$, $V_x = 0$ (3)

[2] at $x = a$, $V_x = 0$ (4)

[3] at $y = 0$, $V_y = 0$ (5)

[4] at $y = b$, $V_y = 0$ (6)

[5] at $z = 0$, $V_z = V_0\, F_0(x, y)$ (7)

[6] at $z = l$, $V_z = V_L\, F_L(x, y)$ (8)

where V_0 and V_L are the driving velocity at the input and output, $F_0(x, y)$=1 at the input and $F_0(x, y)$=0 elsewhere, $F_L(x, y)$=1 at the output and $F_L(x, y)$=0 elsewhere.

According to the above boundary conditions, the sound pressure at the output side becomes

$$P_L = jkZ_wS_w \sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\left\{ \frac{1}{\mu_{m,n}\sinh\left(\mu_{m,n}L\right)}U_0\, D^a_{m,n} + \frac{\cosh\left(\mu_{m,n}L\right)}{\mu_{m,n}\sinh\left(\mu_{m,n}L\right)}U_L\, D^b_{m,n} \right\}\left[\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)\right] \tag{9}$$

where

$$\mu_{m,n} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 - k^2} \tag{10}$$

$$D^a_{m,n} = \frac{4}{m n \pi^2 S_0}\left[\sin\left(\frac{m\pi a_{01}}{a}\right) - \sin\left(\frac{m\pi a_{00}}{a}\right)\right]\left[\sin\left(\frac{n\pi b_{01}}{b}\right) - \sin\left(\frac{n\pi b_{00}}{b}\right)\right] \tag{11}$$

$$D^b_{m,n} = \frac{4}{m n \pi^2 S_L}\left[\sin\left(\frac{m\pi a_{L1}}{a}\right) - \sin\left(\frac{m\pi a_{L0}}{a}\right)\right]\left[\sin\left(\frac{n\pi b_{L1}}{b}\right) - \sin\left(\frac{n\pi b_{L0}}{b}\right)\right] \tag{12}$$

U_0 and U_L are the volume velocity of input and output, respectively. $Z_w = \rho c / S_w$ represents the characteristic acoustic impedance of the cavity, k: wave number, c is the sound velocity.

2.2 Elliptical cylinder

The model of analysis is shown in Fig. 3. A section area S_w and length L of elliptical cavity that has an input and output at both side, the sectional area of them are S_0 and S_L, respectively.

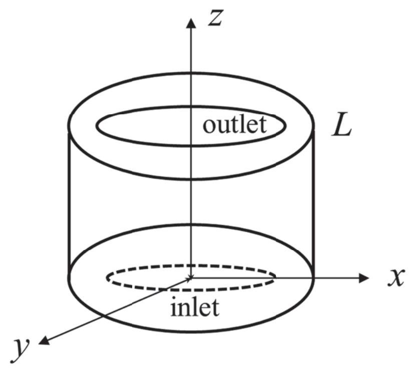

Figure 3 Model analysis of elliptical cylinder

The complete solution of wave equation when expressed in elliptical coordinates is by references (5).

$$\phi = (A_0 \exp(\mu z) + B_0 \exp(-\mu z)) \sum_{m=0}^{\infty} C_m Ce_m(\xi, s)\, ce_m(\eta, s) \tag{13}$$

where $ce_m(\eta, s)$ and $Ce_m(\xi, s)$ are the Mathieu function and modified Mathieu function of mth-order, respectively. Other symbols are 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. The boundary conditions are

[1] at $z = 0$, $V_z = -\partial\phi / \partial z = V_0 F_0(\xi, \eta)$ (14)

[2] at $z = L$, $V_z = -\partial\phi / \partial z = V_L F_L(\xi, \eta)$

(15)

[3] at $\xi = \xi_w$, $V_\xi = -\partial\phi / \partial\xi = 0$ (16)

where

$$F_0(\xi,\eta)=\begin{cases}1 & (0\le\xi\le\xi_{02})\\ 0 & elsewhere\end{cases} \tag{17}$$

$$F_L(\xi,\eta)=\begin{cases}1 & (0\le\xi\le\xi_{L2})\\ 0 & elsewhere\end{cases} \tag{18}$$

From the above boundary conditions ϕ can be determined and the sound pressure at the output piston becomes

$$\begin{aligned}P_{out} &= jk\rho c\phi(\xi,\eta,L)\\ &= jkZ_w\sum_{m=0}^{\infty}\sum_{i=0}^{\infty}\left(U_0\frac{1}{\mu_{m,i}\sinh\mu_{m,i}L}H_{m,i}-U_L\frac{\cosh\mu_{m,i}L}{\mu_{m,i}\sinh\mu_{m,i}L}G_{m,i}\right)Ce_m(\xi,s_{m,i})ce_m(\eta,s_{m,i})\end{aligned} \tag{19}$$

where k is wave-number, $Z_w=\rho c/S_w$, U_0 and U_L are the volume velocity of the input and output section, other symbols are defined by

$$H_{m,i}=\frac{\int_0^{2\pi}\int_0^{\xi_{02}}Ce_m(\xi,s_{m,i})ce_m(\eta,s_{m,i})(\cosh 2\xi-\cos 2\eta)\,d\xi d\eta}{\int_0^{2\pi}\int_0^{\xi_w}Ce_m^2(\xi,s_{m,i})ce_m^2(\eta,s_{m,i})(\cosh 2\xi-\cos 2\eta)\,d\xi d\eta} \tag{20}$$

$$G_{m,i}=\frac{\int_0^{2\pi}\int_0^{\xi_{01}}Ce_m(\xi,s_{m,i})ce_m(\eta,s_{m,i})(\cosh 2\xi-\cos 2\eta)\,d\xi d\eta}{\int_0^{2\pi}\int_0^{\xi_w}Ce_m^2(\xi,s_{m,i})ce_m^2(\eta,s_{m,i})(\cosh 2\xi-\cos 2\eta)\,d\xi d\eta} \tag{21}$$

$$\mu_{m,i}=\frac{1}{a_w}\sqrt{\lambda_{m,i}^2-(ka_w)^2} \tag{22}$$

3. RESULTS AND DISCUSSION

In the case of elliptical cylinder, the first term of Eq. (9) represented the sound pressure component of plane wave. P_L is great in the frequencies where the nominator $\sin kL$ becomes zero, namely

$$kL=\eta\pi \therefore f=\eta\frac{c}{2L}\quad(\eta=1,2,.....) \tag{23}$$

The frequency illustrated in Eq. (23) is called as the resonance frequency of plane wave. The second term of Eq. (9) represented the sound pressure component of higher-order mode. P_L is great in the frequencies where the nominator $\sinh\mu_{m,i}L$ becomes zero, namely

$$\mu_{m,i}L=j\eta\pi \qquad \therefore\quad f_{m,i}=\frac{c}{2\pi a_w}\sqrt{\lambda_{m,i}{}^2+\left(\frac{\eta\pi a_w}{L}\right)^2}\quad(\eta=0,1,.....) \tag{24}$$

Similarly, in the case of rectangular cube, resonance frequency of plan wave is the same as Eq. (23). The resonance frequency of higher-order modes are given as following.

$$f_{m,n}=\frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2+\left(\frac{\eta\pi}{L}\right)^2}\quad(\eta=0,1,.....) \tag{25}$$

For the purpose of attaching SVHU inside the wall, the cavity can be fabricated by a rectangular cube or elliptical cylinder form. Be aware that the shape of the cavity has to be selected based on the fundamental feature such as low resonance levels, less of resonance generation, high frequency of resonance in order to avoid reducing a size of the unit due to the use of a thick sound absorbing material. Furthermore, ideally, the resonance frequency should be out of the range where human ears are most sensitive.

The calculation of the first resonance frequencies is performed by Eq. (24) and Eq. (25) for a rectangular cube and two elliptical cylinders with the same volume. The dimension of the rectangular cube is a=0.37m, b=0.17m and L=0.6m. The dimension of the elliptical cylinder is aw=0.18m, bw=0.11m and L=0.6m. The calculation results are shown in Fig. 4. It is clear that an elliptical cylinder is advantageous in terms of less resonance generation.

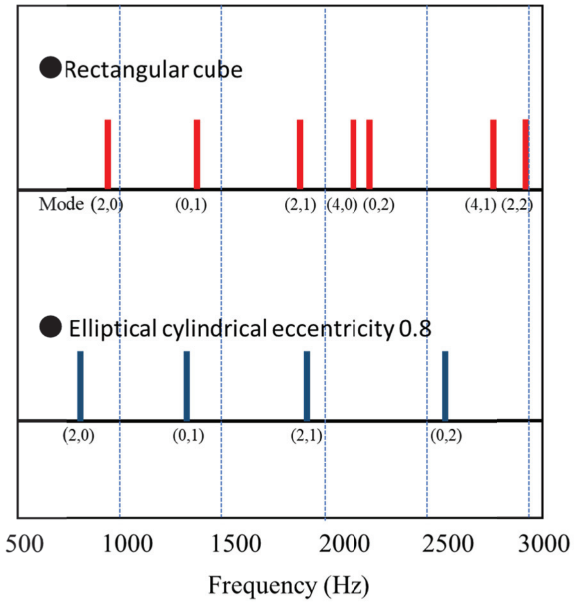

Figure 4 The first resonance frequencies of higher order mode

4. CONCLUSION

This paper describes the design of the soundproof ventilation unit for installation inside the wall of a house. The rectangular cube or elliptic cylinder form is reasonable as the unit shape for this purpose. The sound pressure propagating in the unit has a standing wave and higher-order mode wave components. The noise tends to increase in the frequency range due to higher order mode resonance. At first, the theoretical calculations of the sound pressure inside the rectangular cube and elliptic cylinder are carried out by solving the wave equation. Next, the resonance frequencies of the higher-order mode wave component are calculated for a rectangular cube or elliptic cylinder of the same volume. In order to have more soundproofing efficient, the comparison of resonance frequencies of the higher-order mode wave between the rectangular cube and elliptic cylinder is also discussed lead to the conclusion that using the elliptical cylinder in the unit will be more soundproofing efficient.

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