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NOISE REDUCTION OF AN ENCLOSED CAVITY BY MEANS OF AIR-GAP SYSTEMS

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ABSTRACT−The objective of this paper is to introduce the noise reduction characteristics of a double gap system, which is composed of two air-gaps and two partition sheets. The resonance of acoustic modes of an enclosed cavity can be effectively suppressed by installing the double gap system in the cavity. It is revealed from a simple, one-dimensional model that the double gap system is more effective than the single gap system that consists of one air-gap and one partition sheet, in that the former requires a smaller space than the latter. Finally, these theoretical conclusions are verified by comparison experiments using an actually manufactured enclosed cavity, of which the boundary surfaces are made of thick panels that can be assumed as rigid walls.

KEY WORDS : Noise reduction, Passenger compartment, Gap resonator, Helmholtz resonator, Resonance, Cavity

1. INTRODUCTION

The single air-gap resonator, composed of one air-gap and one partition sheet, was studied in the authors previous researches (Kang *et al.*, 2000; Kang and Lee, 2003). It was revealed that this resonator acts as the conventional Helmholtz resonator (Chanaud, 1994; Chanaud, 1997; Dickey and Selamet, 1996; Selamet *et al.*, 1997; Selamet and Ji, 1997) that suppresses a resonant noise at its resonant frequency, and that the resonant frequency of the single gap resonator is inversely proportional to the gap thickness. It was, therefore, concluded that larger gap thickness is required to suppress a resonant noise peak in lower frequency range.

Absorbent materials have been used to control interior noises (booming noises) in a passenger vehicle. Although higher frequency noises can be relatively easily controlled by the use of a small amount of absorbent materials, lower frequency noises are almost impossible to control (Ko *et al.*, 2003). This is because too much amount of absorbent materials are needed in case of the latter. For example, absorbent materials of 340 mm-thickness are at least required to control 100 Hz-noise, based on the report that absorbent materials of 1/10 times as great as the wavelength of a target noise is required to effectively control the target noise (Reynold, 1981).

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As a solution of this problem, the authors have introduced two types of air-gap resonators (single gap resonator and double gap resonator), which can be installed below the roof metal sheet in a passenger vehicle as shown Figure 1. In particular, it was mentioned in the second paper (Kang and Lee, 2003) that there might be the possibility that the double gap resonator may control a lower frequency noise better than the single gap resonator with the same gap thickness. However, no verification was presented and only theoretical simulations using a one-dimensional model were performed.

In this paper, a simple review on the air-gap resonators is first summarized and then verification experiments for the confirmation of the possibility aforementioned are presented.

2. SIMPLE REVIEW ON THE AIR-GAP RESONATORS

2.1. One-dimensional Model for the Double Gap System

Figure 2(a) shows an enclosed cavity with the double gap resonator, composed of two partition sheets and two air gaps. Note that, if the 1st partition sheet is removed, the double gap resonator becomes a single gap resonator. It may be imagined that the gap resonator will influence vertical standing waves formed in the direction of the height of the cavity and, as the result, it will suppress the resonance of the vertical acoustic modes of the cavity. In order to investigate the validity of this idea and simulate

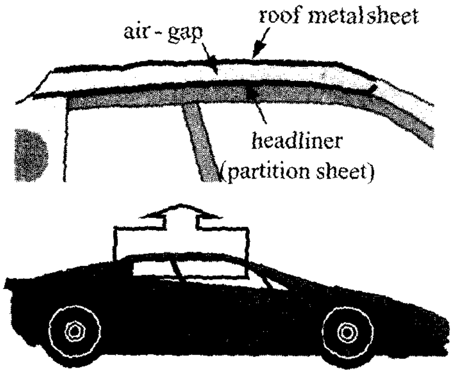
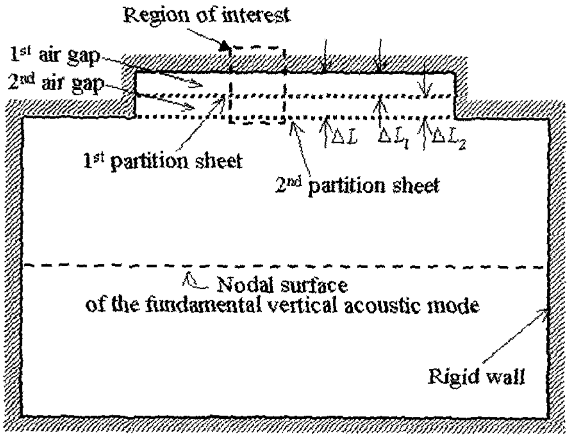
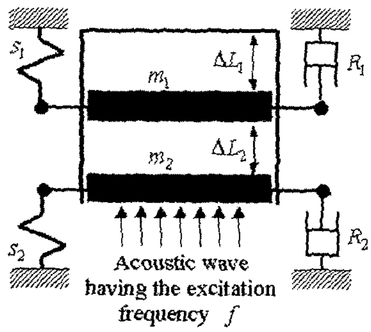


Figure 1. Air-gap resonator in a passenger vehicle.



(a) Double gap resonator installed on the upper boundary surface of an enclosed cavity.



(b) Theoretical model designed from the region of interest indicated in Figure 2(a).

Figure 2. Acoustic cavity with the double gap resonator and its theoretical model.

the complex double gap system, a simple, one-dimensional model shown in Figure 2(b) is used.

2.2. Closed Form Resonant Frequencies of the Air-gap Systems

Under the assumption that the 1st partition sheet is the same as the 2nd partition sheet in material properties in Figure 2(a), i.e., $m_1=m_2\equiv m$, $s_1=s_2\equiv s$ and $R_1=R_2\equiv R$ in Figure 2(b), the resonant frequencies of the double gap resonator shown in Figure 2(b) can be calculated from

$$f_R=\sqrt{f_p^2+\frac{\rho c^2}{4\pi^2\rho_p\Delta L}G}, \qquad (1)$$

where $f_p=1/2\pi\sqrt{s/m}$ denotes the natural frequency of the mass-spring system in Figure 2(b); ρ_p and ΔL denote the surface density of the partition sheet and the total gap thickness ($\Delta L=\Delta L_1+\Delta L_2$), respectively; ρ and c denote the density of air (1.21 kg/m^3) and the speed of sound (344 m/s), respectively; finally, G is given by

$$G\approx\frac{1+\gamma\pm\sqrt{5\gamma^2-2\gamma+1}}{2\gamma(1-\gamma)}, \qquad (2)$$

$$\equiv G_d^{(1)} \text{ and } G_d^{(2)},\ G_d^{(1)}<G_d^{(2)}$$

with $\gamma=\Delta L_1/\Delta L$. Note that γ represents the proportion of the upper gap thickness to the total gap thickness and it is in the range of $0<\gamma<1$.

In the particular case that the first partition sheet is removed in Figure 2(a), that is, in case of the single gap resonator, its resonant frequency can also be calculated using Equation (1) with

$$G\approx 1\equiv G_s \qquad (3)$$

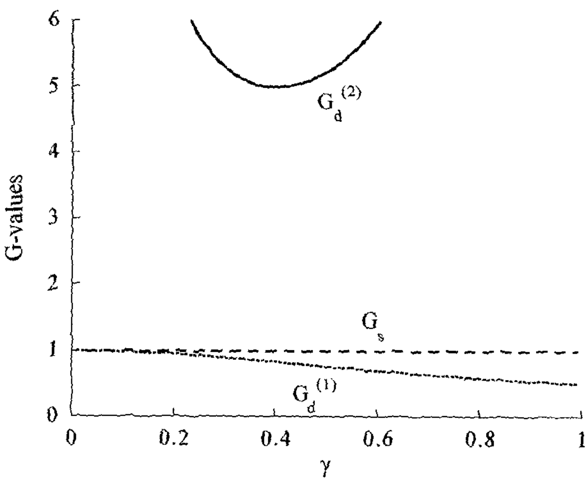


Figure 3. Comparison of magnitudes of $G_d^{(1)}$, $G_d^{(2)}$ and G_s *in the range of* $0<\gamma<1$.

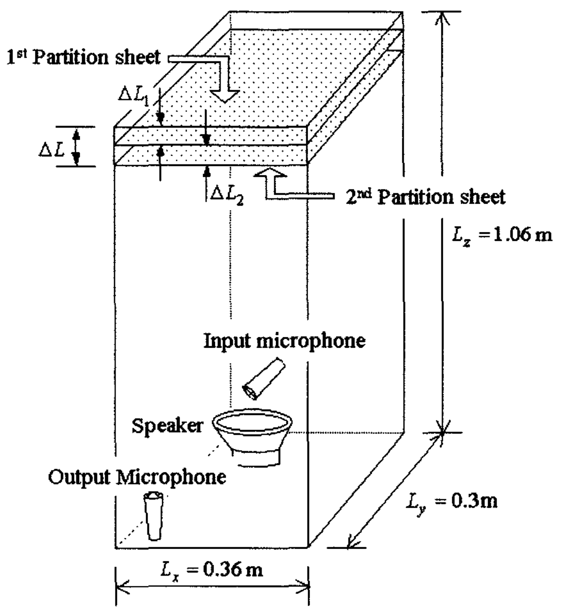


Figure 4. Experimental set-up for evaluating prediction results.

3. NEW WORK ON THE AIR-GAP RESONATORS

3.1. Gap Thickness for Suppressing a Target Noise

To suppress a narrowband noise generated in an enclosed cavity by using the air-gap resonator, the resonant frequency, f_R, should be tuned to a peak frequency, f_T, of the narrowband noise. Also, a value of the gap thickness to tune f_R to f_T can be calculated from Equation (4), which has been changed from Equation (1).

$$\Delta L_{tuned}=\frac{\rho c^2 G}{4\pi^2\rho_p(f_T^2-f_p^2)}, \quad (4)$$

where $G=G_d^{(1)}$ or $G_d^{(2)}$ for the double gap system and $G=G_s=1$ for the single gap system. In the paper, the gap thickness is tuned so as to suppress the target noise with peak frequency f_T, and ΔL_{tuned} is termed the *tuned gap thickness*. As known in Equation (4), two *tuned gap thicknesses* may be calculated for a double gap resonator. However, the tuned gap thickness calculated using $G=G_d^{(2)}$ is not chosen because it is larger than the other. Note that it is more effective to use a smaller gap for suppressing a target noise.

Now, which of the single gap resonator or the double one needs less *tuned gap thickness* is examined. Using Equation (4), the tuned gap thickness for the single gap resonator is given by

$$\Delta L_{tuned}^{single}=\frac{\rho c^2 G_s}{4\pi^2\rho_p(f_T^2-f_p^2)}, \quad (5)$$

and the tuned gap thickness for the double gap resonator is given by

$$\Delta L_{tuned}^{double}=\frac{\rho c^2 G_d^{(1)}}{4\pi^2\rho_p(f_T^2-f_p^2)}. \quad (6)$$

Owing to $G_d^{(1)}<G_s<G_d^{(2)}$ as shown in Figure 3, $\Delta L_{tuned}^{double}$ is smaller than $\Delta L_{tuned}^{single}$.

It may be said from the above fact that the double gap resonator is more effective than the single gap resonator because the former needs less *tuned gap thickness* than the latter. From Equations (5, 6), a relationship between $\Delta L_{tuned}^{single}$ and $\Delta L_{tuned}^{double}$ can be obtained as follows.

$$\Delta L_{tuned}^{double}=\Delta L_{tuned}^{single}\times G_d^{(1)}, \quad (7)$$

where note that $G_d^{(1)}<1$ in the range of $0<\gamma<1$.

3.2. Prediction and Verification Experiments

In this section, the usefulness and validity of Equation (4) is verified by comparing prediction results with experiment results. For verification experiments, a box-shaped enclosed cavity was manufactured and acoustic frequency response functions (AFRFs) have been measured using the experimental set-up shown in Figure 4. The fundamental natural frequencies and surface density of the partition sheet used commonly for the first and second partition sheets are measured as 78 Hz and 1.7 kg/m^2, which correspond to f_p and ρ_p in Equation (4), respectively.

For comparison tests, an acoustic response of the case that the first and second partition sheets are both removed has been measured (see Figure 5). Four dominant peaks labeled by 165 Hz, 340 Hz, 517 Hz and 695 Hz in Figure 5 have been created thanks to the resonance of the first four vertical modes of which standing waves form in the z direction. In the paper, 165 Hz peak is considered as a target noise peak. Note that, if one tries to suppress 165 Hz peak effectively, absorbent materials of 210 mm thickness are at least required.

3.2.1. Predictions

Prior to experiments for evaluating the single gap resonator and the double gap resonator, values of the tuned gap thickness for the two resonators will be predicted using Equations (5, 7)

(1) Single gap resonator

Table 1. Values of parameters used for determining ΔL_{tuned}.

f_p	ρ_p	f_T	ρ	c
78 Hz	1.7 kg/m^2	165 Hz	1.21 kg/m^3	344 m/s

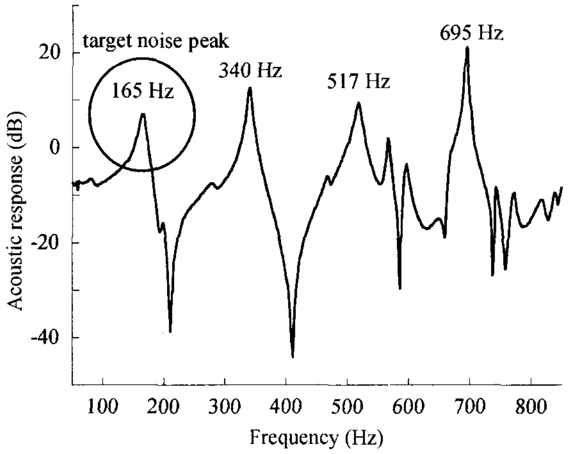


Figure 5. Acoustic response when no resonator is installed.

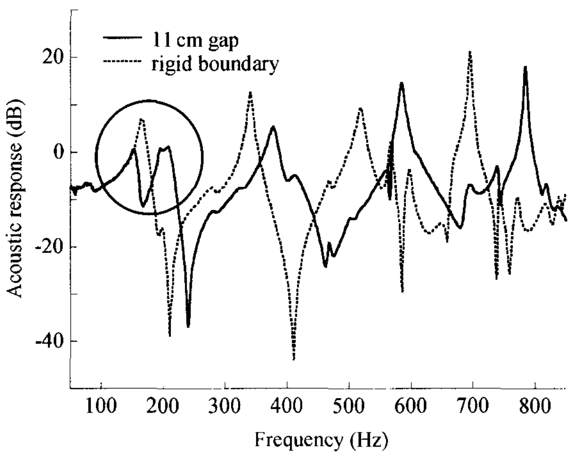


Figure 6. Acoustic response when ΔL=11 cm.

A value of the tuned gap thickness for 165 Hz peak when the single gap resonator is installed in Figure 4 can be predicted by Equation (5). Note that the single gap resonator is embodied by removing the 1st partition sheet. By substituting values of Table 1 and G_s=1 into Equation (5), $\Delta L_{tuned}^{single}$ has been found to be approximately 10 cm. It should be noted that this value is less than the half of the thickness (210 mm) required when absorbent materials are used.

(2) Double gap resonator
By the use of Equation (7), a value of the tuned gap thickness for 165 Hz peak has been obtained as $\Delta L_{tuned}^{double}=10\times G_d^{(1)}$ cm. On considering the special case that $\Delta L_1=\Delta L_2$ (i.e., γ=0.5), $G_d^{(1)}$ is calculated as $3-\sqrt{5}$ by Equation (2). Finally, the tuned gap thickness for the doubles gap resonator is found to be approximately 75 mm.

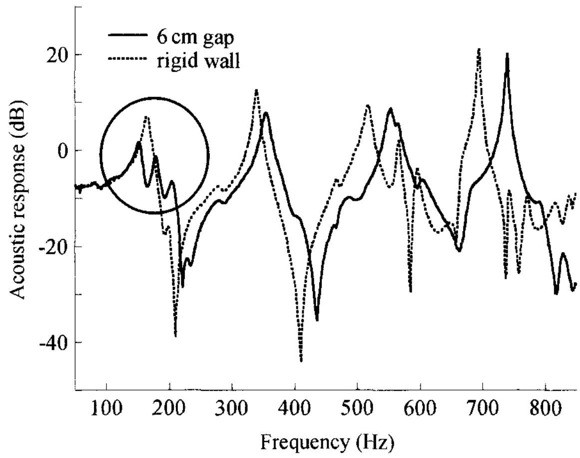


Figure 7. Acoustic response when ΔL=6 cm and γ=0.5.

3.2.2. Experiments
In the experiments, the gap thickness of the single gap resonator or the double gap resonator has been increased from 0 mm to 130 mm by 5 mm, to find the tuned gap thickness for suppressing the 165 Hz peak indicated in Figure 5.

(1) Single gap resonator
In the case that the single gap resonator is installed in the cavity, the 165 Hz peak has been suppressed when 11 cm gap is given (See Figure 6). This experimental result agrees well with the prediction results (10 cm). As a result, it may be said that Equation (4) presented to predict the *tuned gap thickness* is valid.

(2) Double gap resonator
In the case that the double gap resonator with $\Delta L_1=\Delta L_2$ is installed, it has been revealed from Figure 7 that the 165 Hz peak is suppressed when the gap thickness becomes 60 mm. This experimental result is a little smaller than the prediction result (76 mm). It may, however, be said that Equation (4) presented for the tuned gap thickness of the double gap resonator is reasonable because it can be employed as an important guideline when one tries to determine a value of the tuned gap thickness in real systems.

5. CONCLUSION

In the paper, it has been verified by simulations and experiments that the double gap resonator has more excellent performance than the single gap thickness. Also, the comparison between prediction results and experiment results has revealed that Equation (4) almost accurately predicts the tuned gap thickness to suppress a target noise.

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