한국소음진동공학회논문집 제16권 제11호, pp. 1140~1148, 2006.

Study on Transmission Loss in Smart Panel Using Admittance
어드미턴스를 이용한 지능패널의 투과손실에 대한 연구

Lijie Zhao, Heung Soo Kim and Jaehwan Kim
Lijie Zhao* · 김 흥 수† · 김 재 환**

(Received September 8, 2006 ; Accepted November 7, 2006)

Key Words : Admittance(어드미턴스), Electro-mechanical Coupling(전기-기계 연성), Piezoelectric Shunt Damping(압전션트댐핑), Transmission Loss(투고손실)

ABSTRACT

In this paper, transmission loss of smart panel was investigated using piezoelectric shunt damping. Admittance of piezoelectric system was introduced to represent electro-mechanical coupling of smart panel and to predict the performance of shunt damping. Finite element method was used to obtain numerical admittance. In order to illuminate the effect of noise reduction in the shunt system, transmission loss of the smart panel was investigated. Two models were considered to show the relation between admittance and transmission loss of smart panel. It was observed that admittance of piezoelectric system could be used as a design index of smart panel.

요 약

이 논문에서는 압전션트를 이용한 지능패널의 투과 손실에 대해 연구하였다. 지능패널의 전기-기계 연성 계수인 어드미턴스를 도입하여 션트 댐핑의 성능을 예측하였다. 유한요소를 사용하여 수치적인 어드미턴스를 계산하였고 실험결과와 비교하였다. 압전션트 시스템에서 소음 저감의 효과를 보여주기 위해 지능패널의 투과 손실을 연구하였다. 두 개의 모델을 사용하여 어드미턴스와 투과 손실과의 관계를 규명하였고 이 관계에서 어드미턴스를 지능패널의 설계 지수로 사용가능함을 발견하였다.

1. Introduction

Noise radiating from vibrating structures is a vital problem in the field of engineering. Many efforts have been conducted to reduce noise of structure. Since passive piezoelectric shunt system is simple, compact and low cost compared with active damping technology, piezoelectric shunt damping has been spotlighted in the field of vibration reduction [1~3].

The piezoelectric shunt damping uses the principles of energy transfer and dissipation. Energy transfer from mechanical vibration into electrical energy is occurred in piezo ceramic patches bonded on the structures. The transferred energy is dissipated by heat through resistor in shunt circuit networked to the structure[2,3]. Generally, piezoelectric shunt system consists of host plate on which piezo ceramic patches are bonded and electric shunt circuit networked to the piezoelectric structure, termed as smart

† 책임저자 ; 정회원, 인하대학교 기계공학부
E-mail : heugnsookim@inha.ac.kr
Tel : (032)860-8256, Fax : (032)868-1716
* 인하대학교 대학원 기계공학과
** 정회원, 인하대학교 기계공학부

panel. In order to dissipate external vibration or acoustical energy efficiently, piezoelectric structure must be constructed to generate more charges on the surface of piezo ceramic patches. So far, most researches have been concentrated on piezoelectric shunt circuit to improve the performance of shunt system[(4~6)].

In this paper, admittance is introduced to predict the performance of piezoelectric shunt damping. Admittance represents electro-mechanical coupling of piezoelectric system. The relation between admittance and piezoelectric shunt performance is investigated by studying vibration and noise reduction of smart panel.

2. Numerical Analysis

Smart panel is configured as shown in Fig. 1. A piezo ceramic patch is bonded on the surface of host plate and networked to the shunt circuit. Smart panel is used to reduce the level of transmitted sound.

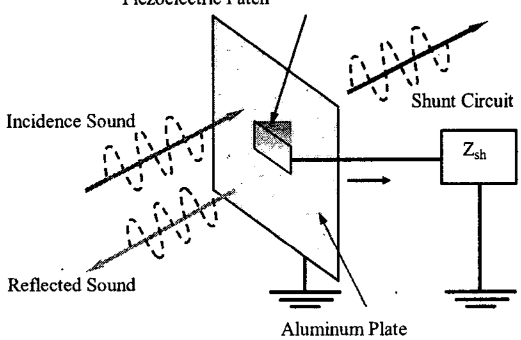


Fig. 1 Schematic diagram of piezoelectric structure

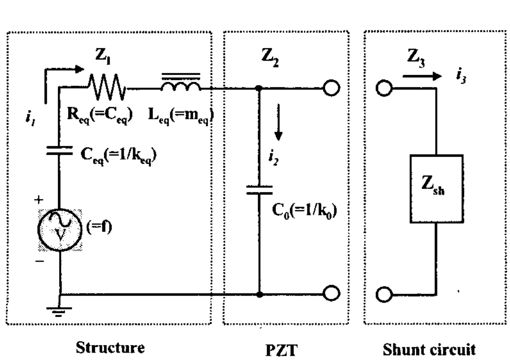


Fig. 2 Equivalent circuit of the smart panel

2.1 Admittance and Dissipated Energy

To improve the performance of smart panel, it is required the high energy conversion rate from mechanical energy of piezoelectric structure to electrical energy. To achieve this, electro-mechanical coupling of piezoelectric structure must be analyzed, which can be characterized by admittance of the given system[(7)].

According to Hagood and Flotow[(1)], piezoelectric structure can be represented as an equivalent circuit as shown in Fig. 2. The electrical impedance of arbitrary piezoelectric structures can be measured easily. According to Fig. 2, the induced power of the system under external excitation is defined as follows.

$$P_{in} = \frac{1}{2}\left|V \cdot i_1^*\right| = \frac{1}{2}\left|\frac{i}{Y} \cdot i_1^*\right| = \frac{1}{2}\left|\frac{1}{Y}\right| \cdot |i_1|^2 \quad (1)$$

where i_1^* is the complex conjugate of the current i_1 and Y is the admittance of the piezoelectric patch. Meanwhile, the dissipated power at the shunt circuit can be described as

$$\begin{aligned} P_D &= \frac{1}{2}\left|V_2 \cdot i_3^*\right| = \frac{1}{2}\left|(\mathrm{Re}(Z_3)\cdot i_3)\cdot i_3^*\right| = \frac{1}{2}\mathrm{Re}(Z_3)\cdot|i_3|^2 \\ &= \frac{1}{2}\mathrm{Re}(Z_3)\cdot\left|\frac{Z_2}{Z_2+Z_3}\right|^2\cdot|i_O|^2 \\ &= \frac{1}{2}\mathrm{Re}(Z_3)\cdot\left|\frac{Z_2}{Z_2+Z_3}\right|^2\cdot|V_O|^2\cdot|Y_{12}|^2 \end{aligned} \quad (2)$$

where, $Y_{12} = (Z_1 + Z_2)^{-1}$ represents admittance of piezoelectric structure in open circuit. Z_1, Z_2, Z_3 represent the impedances in equivalent circuit. The voltage, V_O, represents voltage of piezoelectric patch in open circuit and is independent constant. The dissipated power is only a function of admittance in Eq. (2). Therefore, the reduction of vibration in the piezoelectric shunt system is dependent on admittance of piezoelectric structure and admittance can be regarded as a performance index in designing smart panel.

2.2 Admittance Analysis

Admittance of piezoelectric structure can be obtained by Electro-mechanical Impedance (EMI) model(8) or the finite element method(9~11). Finite element analysis is an effective method for analysis of structural response, because it is applicable to arbitrarily shapes and geometries. The equations of motion for the piezoelectric structure in matrix form are expressed as follows(12).

$$\begin{Bmatrix} [M] & [0] \\ [0] & [0] \end{Bmatrix}\begin{Bmatrix} [\ddot{u}] \\ [\ddot{\phi}] \end{Bmatrix} + \begin{Bmatrix} [D] & [0] \\ [0] & [0] \end{Bmatrix}\begin{Bmatrix} [\dot{u}] \\ [\dot{\phi}] \end{Bmatrix} + \begin{Bmatrix} [K] & [K_{u\phi}] \\ [K_{u\phi}]^t & [K_{\phi}] \end{Bmatrix}\begin{Bmatrix} [u] \\ [\phi] \end{Bmatrix} = \begin{Bmatrix} [F] \\ [Q] \end{Bmatrix} \tag{3}$$

$$|Y| = \left|\frac{I}{V}\right|, \qquad I = j\omega\sum_i Q_i \tag{4}$$

$$Y = G + jB \tag{5}$$

where,

[F], [u] : vector of nodal structural forces and mechanical displacements

[M], [D], [K] : structural mass, damping and stiffness matrix

[Q], [ϕ] : vector of nodal electrical charges and potential

$[K_{u\phi}]$, $[K_{\phi}]$: piezoelectric coupling and dielectric conductivity matrix, "t" : transposed

I, V : current and voltage

Y, G, B : admittance, conductance, susceptance

Q_i : the point charge of the i-th node on the electrode.

To formulate above equation, commercial finite element package, ANSYS, was used. From the above equations, mode shapes and natural frequencies of smart panel were extracted and admittances of piezoelectric patch were obtained.

In the present study, two different configurations of smart panel were studied. The size of aluminum plate is 300 mm×300 mm×0.5 mm. The piezo patch is surface-bonded as shown in Fig. 1, but two different sizes are considered. The size of piezo patch 100 mm×50 mm×0.5 mm is defined as model 1 and 100 mm×100 mm×0.5 mm patch is defined as model 2.

The strong radiation modes of the smart panel were first obtained by ANSYS. The natural frequencies were extracted from modal analysis and first two natural frequencies of radiation mode are presented in Table 1. The admittances of the smart panel were obtained from harmonic analysis as shown in Eq. (3) and (4). The admittances at natural frequencies were extracted to calculate the vibration energy at resonance. Admittance is consisted of real part, conductance and imaginary part, susceptance. The magnitude of electro-mechanical coupling is represented by conductance and Fig. 3 shows the conductances of models1 and 2. From the result, model 2 generates more charges than model 1 on the surface of piezo patch.

3. Setup of the Experimental System

In order to correlate the results of numerical analysis, three experimental systems were constructed to examine the shunt performance and noise reduction through switching on/off the shunt circuit.

3.1 Admittance Test

The admittances for model 1 and 2 were measured by using the impedance analyzer (HP4192A). The experimental setup is presented in Fig. 4. The admittances were measured at open circuit state.

According to the poling direction, the positive electrode of the impedance analyzer was connected with the up surface of the piezoelectric patch that was away from host plate. The negative electrode of the impedance analyzer was connected with the host plate.

Table 1 Natural frequencies of model 1 and model 2

Model	Finite element method
	Frequency (Hz)
100 mm×50 mm	129
	502
100 mm×100 mm	125
	505

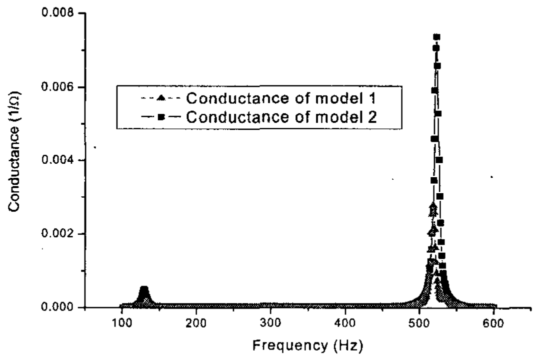


Fig. 3 Conductance of model 1 and model 2

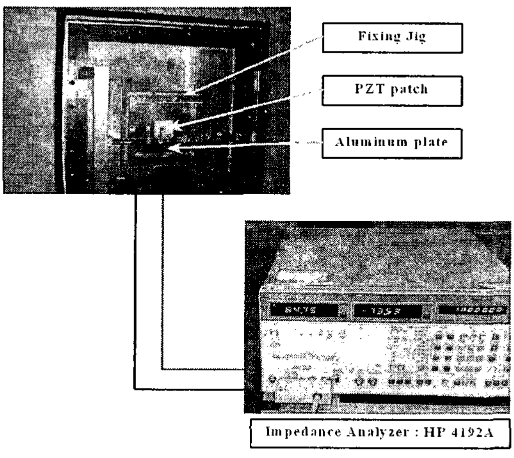


Fig. 4 Experimental setups for admittance measurement

3.2 Shunt Damping in Smart Panel

For the sake of testing the performance of shunt damping, experimental apparatus was constructed as shown in Fig. 5. An actuating piezo patch (50 mm×50 mm×0.5 mm) is bonded on the center place of one side of the panel. An accelerometer (charge accelerometer type 4374, B&K) is attached on the surface of the shunting piezo patch. Tuning the value of inductance in the shunt circuit, the real resonance of the shunt circuit can be found. Tuning the value of load resistor in the shunt circuit, the optimal damping can be achieved.

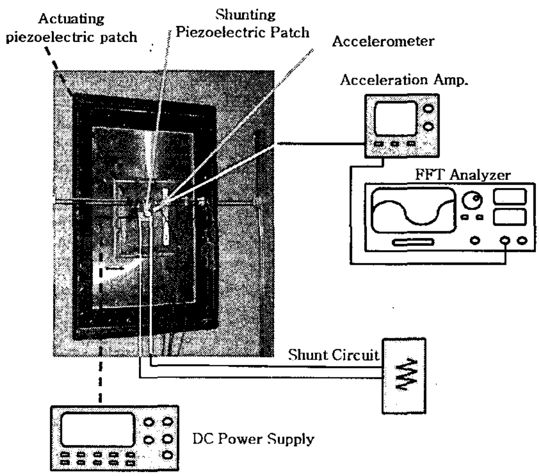


Fig. 5 Experimental setup for shunt damping

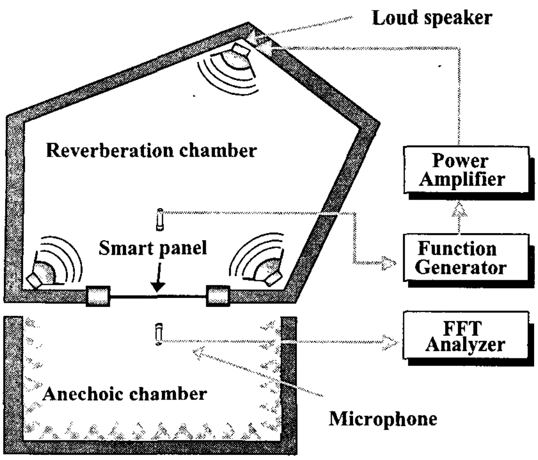


Fig. 6 Schematic for transmission loss test

The testing devices include PORTABLE FFT ANALYZER CF-3200 manufactured by ONO SAKK company.

3.3 Transmission Loss in Smart Panel

To test the transmission loss of the smart panel with shunt circuit, a standard facility was built according to SAE J1400. The schematic is shown in Fig. 6. The transmission loss test facility includes two adjacent rooms, a reverberation room and a semi-anechoic reception room. A test window is located between the two rooms where smart panels are clamped for testing. Sine sweep plane wave is generated through the loudspeakers in the reverberation room, and the sound pressures, which are reflected and transmitted through the window, are measured by microphones in the reverberation room and the reception room. The testing devices include sound signal amplifier(Inter VI PA-4000 PUBLIC ADDRESS AMPLFIER) for magnifying the source signal and 3560-B-040 FFT analyzer made by B&K company.

4. Results and Discussion

4.1 Correlation of Admittance

According to section 3.1, admittances were measured for model 1 and 2. Comparisons between experimental and numerical conductance of model 1 is presented in Fig. 7. High peaks of conductance are observed at the natural frequencies of first and fifth modes, which represent the strong radiation modes. The natural frequencies obtained by experiments are shifted down 3.1 % and 1.2 % for model 1. Similarly, the excursions are 2.4 % and 1.4 % for model 2 (Table 2). As a result, the conductances and natural frequencies correlate well between numerical and experimental results..

4.2 Shunt Damping Test

In terms of natural frequencies in the experiment, the first and fifth modes of model 1 and 2 were selected as the resonances in the shunt circuit which need tuning to find best shunt damping. Figure 8 shows frequency response function(FRF) of model 1 under switching on/off shunt damping circuit. From the figure, the tested results are observed according to four testing conditions, which are open circuit, short circuit, under damping and optimal damping. At open and short circuit with shunt off, the resonance is shifted a little due to piezoelectric softening effect. After optimal tuning, the optimal damping can be observed and 16 dB vibration reduction is achieved at the first mode. For the fifth mode, 18 dB vibration reduction is achieved after optimal tuning. By means of the same testing process in model 2, 20 dB vibration reduction is achieved at first mode. For the fifth mode, the

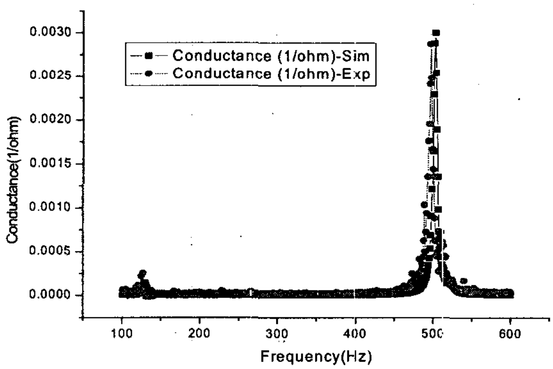


Fig. 7 Comparison of experimental and numerical conductance of model 1

Table 2 Comparison of numerical and experimental natural frequencies

Model	FEM Frequency (Hz)	Experiment Frequency (Hz)	Comparison
100 mm×50 mm	129	125	3.1 %
	502	496	1.2 %
100 mm×100 mm	125	122	2.4 %
	505	512	1.4 %

optimal damping vibration reduction of 22 dB is achieved. Consequently, through the optimal tuning process, model 2 proposes good damping effect comparing to model 1(Table 3).

4.3 Transmission Loss Test

Transmission loss is, "The accumulated decrease in acoustic intensity as an acoustic pressure wave propagates outwards from a source". The term Transmission Loss(TL), or more commonly Sound Reduction Index(SRI) are used to evaluate the reduction in sound level resulting from transmission through the plates. Transmission loss is determined using equation[13].

$$TL = MNR + 10\log(A/S\alpha) \quad (6)$$

where, TL is the transmission loss of the panel, MNR is the measured noise reduction between the reverberation room and reception chamber under sine sweep wave exciting. $S\alpha$ is the Sabine absorption of the reception room, and A is the area of the test window. The expression $10\log(A/S\alpha)$ is constant for any test panel with the same area. Therefore, it can be replaced with a constant correction factor, (CF), Eq. (6) is changed to

$$TL = MNR - CF \quad (7)$$

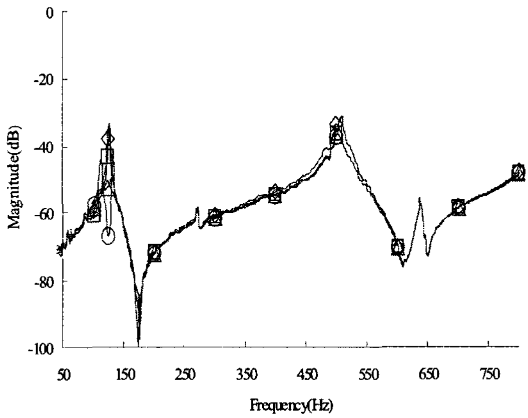
In order to determine this correction factor for the test window, a flexible test panel was made out of 1 mm-thick barrier material to clamp into the test window to calibrate the environment noise level. The transmission loss of the barrier material is directly calculated from the mass-law equation:

$$TL_{calc}(\mathrm{dB}) = 20\log(W) + 20\log(f) - 47.2 \quad (8)$$

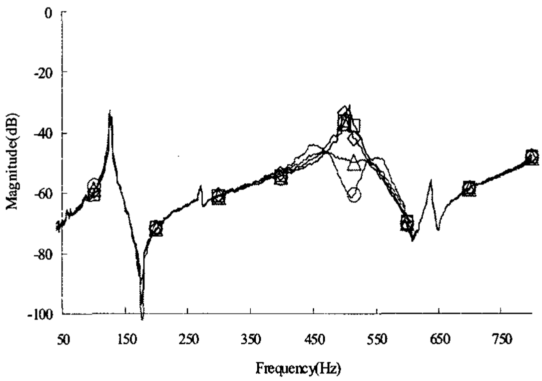
where TL_{calc} is the theoretical transmission loss, W is the weight density of the flexible test panel, and f is the center frequency of the third-octave measurement band. The CF is determined as

$$CF = MNR - TL_{calc} \quad (9)$$

To find transmission loss of model 1 and model 2, Eq. (7) and (9) are used. The MNR values are tested in the light of acoustical test setup in section 3.3. The sine sweep wave was used to excite the models from 1~1250 Hz.



(a) First mode



(b) Fifth mode

Fig. 8 The shunt damping effects of model 1

Table 3 Piezoelectric shunt performance between model 1 and 2

Mode Number	Model 1		Model 2		Improvement
1	125 Hz	−16 dB	122 Hz	−20 dB	25 %
5	496 Hz	−18 dB	512 Hz	−20 dB	25 %

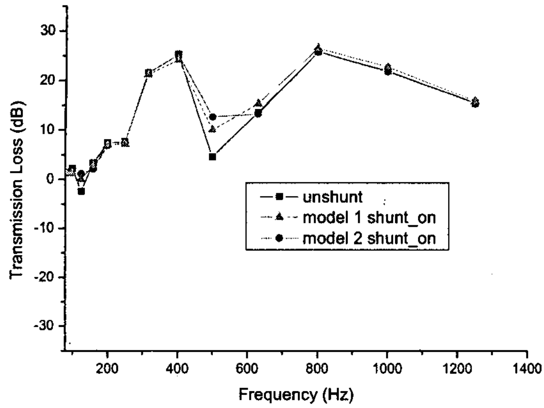


Fig. 9 Transmission loss of model1 and model 2

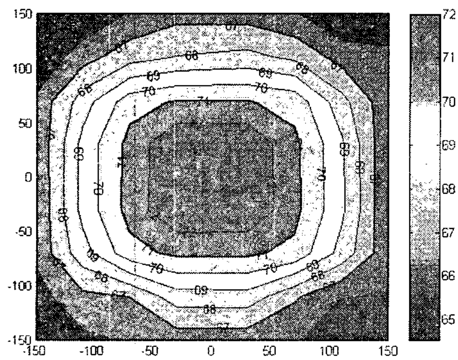
Table 4 Transmission loss between model 1 and 2

Mode Number	Model 1	Model 2	Improvement
1	−2 dB	−3 dB	50 %
5	−5 dB	−8 dB	60 %

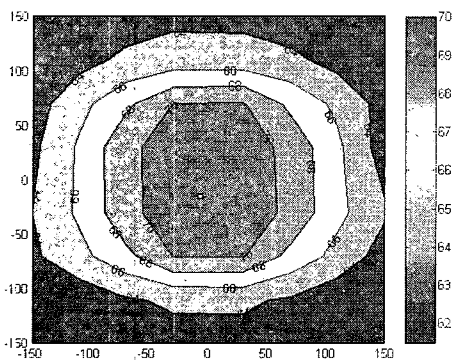
The test results are presented in Fig. 9. From the figure, the transmission loss of model 1 increases 2 dB for the first mode and 5 dB for the fifth mode. However, the transmission loss of model 2 increases 3 dB for the first mode and 8 dB for the fifth mode(Table 4). As result, smart panel with large admittance increases more transmission loss when shunt circuit is switch−on comparing to the shunt circuit switch−off.

4.4 Sound Pressure Distribution

The sound pressure distribution is measured for visualizing the sound pressure level on the smart panel so as to correlate the mode shapes obtained from the finite element code. Making use of the same setup in the transmission loss test, the 64 points were

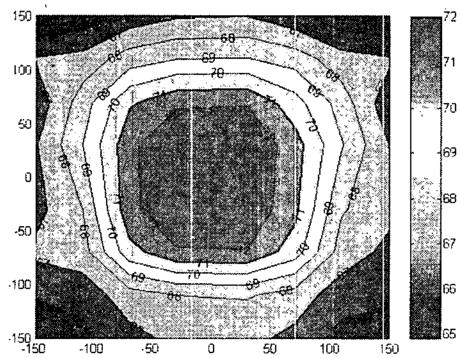


(a) Without shunt

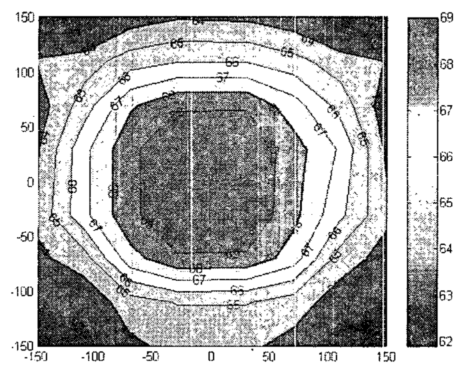


(b) With shunt

Fig. 10 Sound pressure distribution of model 1 at fifth mode



(a) Without shunt



(b) With shunt

Fig. 11 Sound pressure distribution of model 2 at fifth mode selected to arrange the locations of microphones. Exciting the smart panel at different resonances with and without shunt, sound pressure distributions are observed. Figs. 10 and 11 show sound pressure distribution at fifth resonant frequency for model 1 and 2. From the figures, the contour plots of sound pressure distribution provide that the sound pressure is reduced when the shunt circuit on. From the sound pressure values, model 2 can reduce more noise(3 dB) than model 1(2 dB).

5. Conclusions

In this paper, admittance is investigated to find the possibility of the performance index in the design of smart panel. The resonant shunt circuit is networked to the smart panel to suppress noise and to improve the shunt performance. Two models are studied to correlate admittance, shunt performance as well as noise reduction. Four experiments were executed to correlate admittance and verify shunt damping, transmission loss and sound pressure distribution. The result of admittances correlate well comparing with numerical and experimental values. The shunt damping is improved as 25 % in first mode and 22 % in fifth mode through comparing model 1 and model 2. Transmission loss tests for model 1 and model 2 show the transmission loss can be increased 50 % for the first mode and 30 % for the fifth mode. Sound pressure distributions show model 2 makes more sound reduction than model 1 at the radiating frequencies.

It is concluded that the performance of smart panel can be predicted by analyzing admittance of piezoelectric system and admittance can be used as a design index of smart panel. However, the mathematical relation between admittance and the performance of smart panel to predict damped system response or noise reduction is not realized. Therefore, it is remarked that the exact relation between admittance and the performance of smart panel will be undertaken as a second phase of this study.

Acknowledgement

This work was supported by the Creative Research Initiatives Program of Korea Science and Engineering Foundation(KOSEF).

References

(1) Hagood, N. W. and Flotow, A. V., 1991, "Damping of Structural Vibrations with Piezoelectric Material and Passive Electrical Networks", J. Sound Vib. Vol. 146, pp. 243~268.

(2) Law, H. H., Rossiter, P. L., Simon, G. P. and Koss, L. L., 1996, "Characterization of Mechanical Vibration Damping by Piezoelectric Materials", J. and Vib. Vol. 197. No. 4, pp. 489~513.

(3) Moheimani, S. O. R. 2003, "A Survey of Recent Innovations in Vibration Damping and Control Using Shunted Piezoelectric Transducers", IEEE Transactions On Control Systems Technology, Vol. 11. No. 4, pp. 482~494.

(4) Lesieutre, G. A., 1998, "Vibration Damping and Control Using Shunted Piezoelectric Materials", The Shock and Vibration Digest, Vol. 30. No. 3, pp. 187~195.

(5) Tsai, M. S. and Wang, K. W., 1999, "On The Structural Damping Characteristics of Active Piezoelectric Actuators with Passive Shunt", Journal of Sound and Vibration. Vol. 221. pp. 1~22.

(6) Kim, J. H. and Kim, J., 2003, "Multi-mode Noise Reduction of Smart Panel Using Piezoelectric Shunt Damping", Transactions of the Korean Society for Noise and Vibration

Engineering, Vol. 13, No. 4, pp. 300~307.

(7) Rizzoni, G., 1996, "Principles and Applications of Electrical Engineering", 2nd Edition, McGraw-Hill.

(8) Liang, C., Sun, F. P. and Rogers, C. A., 1996, "Electro-mechanical Impedance Modeling of Active Material Systems", Smart Materials and Structures, Vol. 5, pp. 171~186.

(9) Powell, D. J. Mould, J. and Wojcik, G. L., 1998, "Dielectric and Mechanical Absorption Mechanisms for Time Frequency Domain Transducer Modeling", IEEE Ultrasonic Symposium Proceedings, Vol. 2, pp. 1019~1024.

(10) Kim, J., Varadan, V. V., Varadan, V. K. and Bao, X. Q., 1996, "Finite-element Modeling of a Smart Cantilever Plate and Comparison with Experiments", Smart Materials and Structures, Vol. 5, pp. 165~170.

(11) Varadan, V. V., Lim, Y. H. and Varadan, V. K., 1996, "Closed Loop Finite-element Modeling of Active/passive Damping in Structural Vibration Control", Smart Materials and Structures, Vol. 5, pp. 685~694.

(12) ANSYS INC., 1999, "ANSYS Theory Manual Ver. 5.5", SAS IP.

(13) Ahmadian, M. and Jeric, K. M., 2001, "On the Application of Shunted Pieceramics for Increasing Acoustic Transmission Loss in Structures", Journal of Sound and Vibration. Vol. 243. No. 2, pp. 347~359.