Multi-mode shunt damping of piezoelectric smart panel for noise reduction

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A piezoelectric smart panel is a plate structure on which a piezoelectric patch is attached with an electrical shunt circuit. When a sound is impinged on the panel structure, the structure vibrates and the attached piezoelectric patch produces an electrical energy, which can be effectively absorbed by the electrical shunt circuit. Since the energy absorption strongly depends on the vibration mode of the panel structure, many patches are required for broadband noise reduction. Thus, we report a multi-mode shunt damping of a smart panel by using a single piezoelectric patch in conjunction with a blocked shunt circuit. Modeling, shunt parameter tuning and implementation of the blocked shunt circuit along with an acoustic test of the panel are explained. A remarkable reduction of the transmitted noise was achieved for multiple modes of the panel. Since this technology has merits in terms of compactness, low cost, robustness and easiness to install, practical applications in many noise problems can be anticipated.

1. INTRODUCTION

Noise reduction of panels is increasingly required in various fields such as aircrafts, vehicles, ships and buildings to provide a comfortable living environment. There are two ways of reducing the noise of panels: active and passive methods. Active control uses sensors and actuators along with a proper control so as to minimize the noise at a certain frequency band. Successful noise reductions have been obtained by using piezoelectric sensors and actuators along with a controller [1]. However, this method becomes infeasible at high frequencies due to the increased complexity of the controller to take into account the many radiating modes of the structure. In contrast, passive control does not bring any complexity and the system, is stable [2]. Also, it is easy to setup with low cost. The most popular approach in passive control is the use of sound absorbing materials. However, since an increasing amount of material is required for effective noise reduction at low frequencies, the passive approach is impractical for low frequency applications.

In order to get over such a limit, a new passive method has been proposed, which is based on piezoelectric shunt damping. Piezoelectric shunt damping has been experimentally demonstrated in an optical system [3]. This system is composed of piezoelectric elements and a simple electrical circuit. The concept of piezoelectric shunt damping is energy conversion and energy absorption, similar to a dynamic absorber of mechanical systems. Recently, an electrical impedance model of piezoelectric structures determined by the measured impedance data was proposed, and the optimal parameter tuning of the shunt circuit was performed based on the maximum energy dissipation near the target frequency [4]. A remarkable suppression of the transmitted noise was achieved for broadband frequencies by utilizing a hybrid concept that combines the use of sound absorbing materials for mid frequency range and piezoelectric shunt damping for low frequency range [5]. However, several piezoelectric patches were used to take into account the multiple vibration modes of the panel. Hollcamp has expanded the theory of piezoelectric shunting for a single mode so that a single piezoelectric element can be used to suppress two modes by optimally designing the shunt parameters [6]. Wu has accomplished a multi-mode shunt damping with a blocking circuit [7]. The blocking circuit consists of one parallel capacitor and inductor anti-resonance circuit. This anti-resonance circuit is designed to produce infinite electrical impedance at the natural frequencies of all other resonant shunt circuits.

In this paper, multi-mode shunt damping of a piezoelectric smart panel is studied for the noise reduction of the panel. On a single piezoelectric patch, a blocked shunt circuit is connected to implement the multi-mode shunt damping (Fig. 1). The tuning process for shunt parameters is based on the electrical impedance model and the maximum energy dissipation method. Implementation of the shunt circuit and the tuning process of the circuit as well as the acoustic test of the panel for noise reduction are addressed.

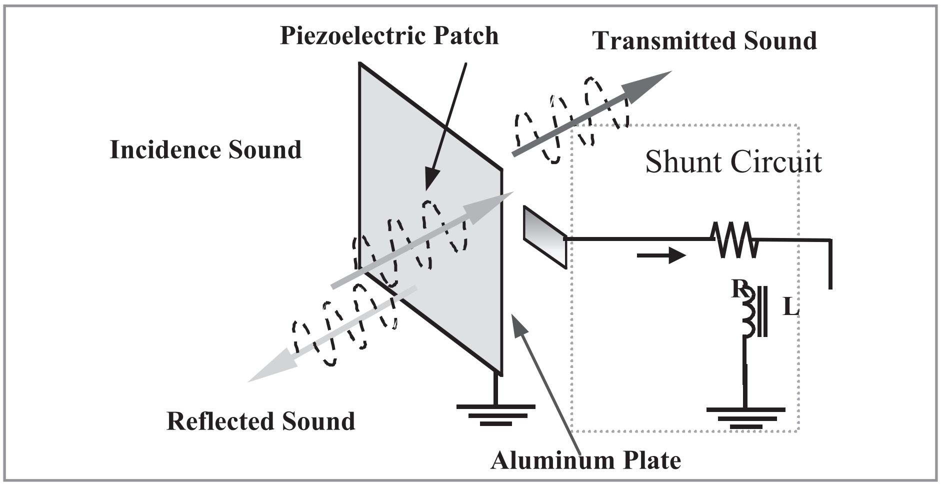


Figure 1. Schematic diagram of piezoelectric smart panels

2. PIEZOELECTRIC SHUNT DAMPING

The concept of piezoelectric shunt damping starts from the energy conversion by the piezoelectric effect. Piezoelectric material converts mechanical energy into electrical energy and vice versa. The converted energy can be absorbed through a shunt circuit. Eventually, the mechanical vibration level is reduced due to the energy absorption. Usually, resonant shunt damping is used to effectively absorb out the energy at the resonance. However to maximize the energy absorption at the resonance frequency of the system, the choice of the optimal inductance and resistance of the shunt circuit is very important. An optimal tuning method for shunt parameters has been developed based on the electrical impedance model. An electrical impedance model of piezoelectric structures has been derived to take into account the coupled structure in conjunction with the shunt circuit. The new shunt parameter tuning method based on the electrical impedance model and the maximum dissipation energy criterion are applied in this paper. This method can be expanded to the problem of multi-mode shunt damping because the same tuning process can be applied for multi-mode in the presence of a blocking circuit.

Piezoelectric materials can be approximately represented as an equivalent electric circuit at a resonance frequency. Van Dyke's model is well known for the equivalent resonance model of piezoelectric materials, which is represented in terms of inherent dielectric capacity, mass, damping and compliance of the material. By invoking the Van Dyke's model, the piezoelectric smart structure on which a piezoelectric patch is bonded along with a shunt circuit can be modeled as shown in Fig. 2. This is an equivalent circuit model for piezoelectric smart panel. The impedance at each branch of the equivalent circuit is described as,

$$\begin{aligned} Z_1(s) &= m_1 s + \frac{k_1}{s} + c_1 = j\omega L_1 + \frac{1}{j\omega C_1} + R_1 \\ Z_2(s) &= \frac{k_2}{s} = \frac{1}{j\omega C_2} \\ Z_3(s) &= Ls + R = j\omega L + R \end{aligned} \tag{1}$$

where, Z_1 is the impedance of the first system, Z_2 and Z_3 express impedances of the secondary system. The total impedance of the equivalent circuit can be written as

$$Z = Z_1 + \frac{Z_2 Z_3}{Z_2 + Z_3} \tag{2}$$

Also, the transfer function can be defined as the ratio of the velocity output to the applied force of the mechanical system. In other words, the transfer function, T_r, can be expressed as in terms of electrical admittance of piezoelectric structure including shunt circuit,

$$T_r = \left|\frac{v}{F}\right| = \left|\frac{i}{V}\right| = \frac{1}{|Z|} = |Y| \tag{3}$$

where v is the velocity, F the force, i the current, V the voltage and Y the admittance. To use the electrical impedance model, coefficients of the Van Dyke's model should be determined. To determine the parameters, the electrical impedance at the piezoelectric patch bonded on the structure is measured by using the impedance analyzer (HP4192A), and the equivalent parameters are extracted from the impedance data by PRAP (Piezoelectric Resonance Analysis Program) [8].

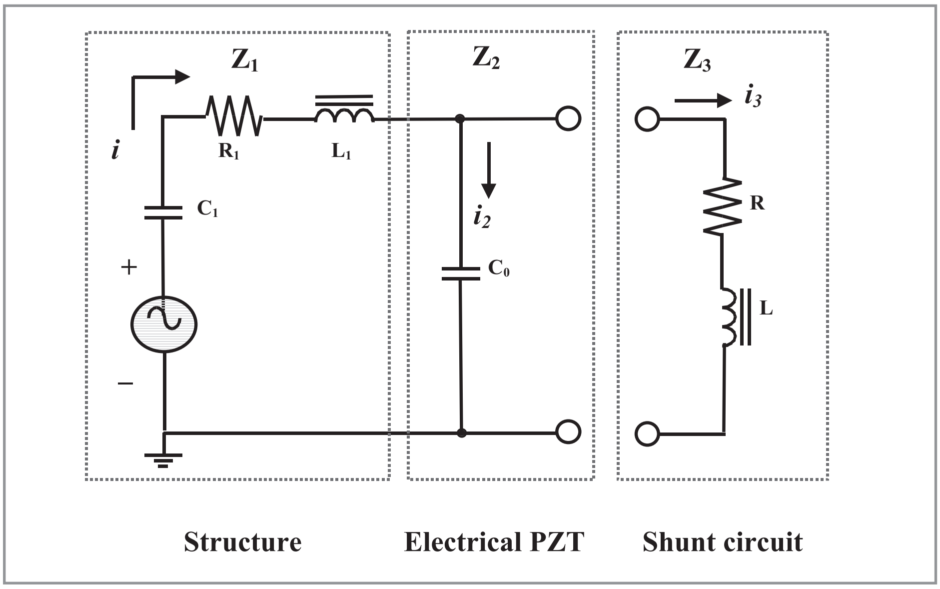


Figure 2. Equivalent electrical circuit of piezoelectric structure

It is essential to maximize the performance of piezoelectric shunt damping by adjusting the parameters of the resonant shunt circuit. The resonant shunt circuit is composed of an inductor and a resistor for single-mode shunt damping.

Therefore, values of each parameter should be optimized to achieve effective noise reduction, which is called the optimal parameter tuning. In this paper, the new parameter tuning method is used, which is based on the maximum dissipated power at the shunt circuit [4].

3. MULTI-MODE SHUNT DAMPING

In general, piezoelectric shunt damping includes a single piezoelectric patch and a shunt circuit for one target frequency. In order to deal with several strong-radiation modes of the panel, several piezoelectric patches should be attached on the structure, as many as the number of modes. However, increasing the number of piezoelectric patches increases the weight of the system. Thus, multi-mode shunt damping with a single piezoelectric patch is very useful for lightweight structures. When a multi-mode shunt circuit is connected to a piezoelectric element, the circuit can resonate at multiple frequencies. In this study, a blocking circuit is adopted to construct a multi-mode shunt circuit [7]. Figure 3 represents the concept of the multi-mode shunt circuit for two resonance modes. R^*_1 and L^*_1 are shunt circuit parameters for the first mode. A blocking circuit is connected to the second shunt circuit such that the blocking circuit blocks the current flow passing through the branch at the first mode. In other words, at the first mode the current flows through the first shunt circuit only since the blocking circuit protects the current at the first mode, and at the second mode the current flows through the second shunt circuit. Of course some current flows through the first shunt circuit at the second mode also.

The tuning process a for multi-mode shunt circuit has three steps. First, optimal shunt parameters are found for a resonance mode by using the new tuning method based on the maximum dissipated power. Secondly, a blocking circuit is designed, which will block the current flow at the resonance mode. Thirdly, other shunt circuit parameters are determined for an additional mode in the presence of the first shunt circuit and the blocking circuit.

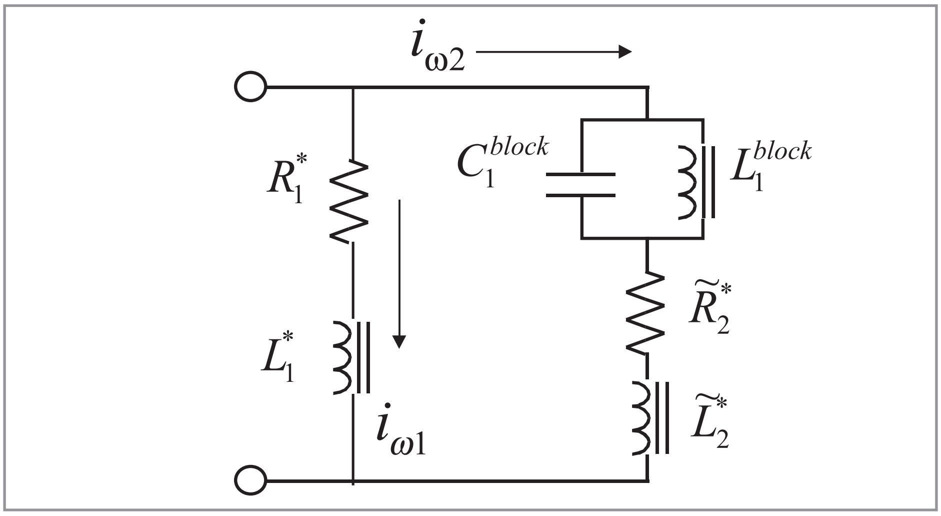


Figure 3. Schematic of shunt circuit for multi-mode

Two resonance modes are investigated in this study. Before determining parameters for multi-mode shunt circuit, shunt parameters for a single mode are employed from the previous tuning process. Next the blocking circuit is designed for the 1st mode by satisfying the resonance equation,

$$\omega_1^2 = \frac{1}{L_1^{block} \cdot C_1^{block}} . \quad (4)$$

While tuned parameters for the first mode and the blocking circuit are kept in the tuning process, optimal parameters for the next resonance mode are found according to the maximum absorbed power.

When the multi-mode shunt circuit is used, however, the complexity of the circuit increases as the number of target modes (n) increases. This is due to the fact that (n-1) blocking circuits are needed at each branch. Also the expression for optimal inductance and resistance becomes complicated. Fortunately, a single piezoelectric patch does not exhibit many modes of the host structure in the dominant noise frequency band. Thus, two or three modes on a single piezoelectric patch are practical. In real applications, a couple of piezoelectric patches should be optimally located to take into account several modes that will radiate noise dominantly.

4. EXPERIMENTS

A piezoelectric smart panel was designed to reduce the transmitted noise at the low frequency range. 300 x 300 x 1.5mm aluminum plate was used as host structure for the panel. To implement the shunt damping, a piezoceramic patch (PZT-5H, 100 x 50 x 0.5mm) was bonded on the plate with epoxy adhesives. Figure. 1 is a schematic diagram of the piezoelectric smart panel. The location of the piezoceramic patch is important for multi-mode shunt damping. Generally, strong radiation modes of a rectangular plate are odd modes such as (1,1) and (1,3), which are the first and second symmetric modes. By locating the piezoceramic patch at the center of the panel, the first and second symmetric modes can be taken into account.

In order to build the shunt circuit, an inductor that has large inductance is necessary. So far, a synthetic inductor has been used to accomplish such a large inductance. However, the use of a synthetic inductor requires an external power to drive OP amps of the circuit. Furthermore, the synthetic inductor circuits can interfere with each other. Therefore, a coil inductor was used instead of a synthetic inductor. A coil inductor does not require external power. Also to implement an independent system of piezoelectric smart panel, the coil inductor can be integrated into the panel without any external power. However, when high inductance value is needed for suppressing low modes of large structures, the use of a synthetic inductor or the use of capacitance in conjunction with the piezoelectric patch might be necessary.

To test the noise reduction performance of piezoelectric smart panel, the transmission measurement from low to high frequencies should be available. For most panel materials the transmission loss has been measured under strict controls [9]. Since this test facility is too expensive, a simple acoustic tunnel has been innovated. Figure 4 shows the schematic diagram of the experimental apparatus for the acoustic panel test. The tunnel is a square tube of 300mm x 300mm and 4m long. It is divided into two sections—upper and lower sections in equal length. A loud speaker is set up at the end of the upper section and anechoic terminator made with wedge is installed at the other end of lower section. Specially designed flange is provided where two sections are met such that smart panels can be mounted in both. The function generator (Wavetek178) generates a sine sweep signal and the signal is fed to the loud speaker through the power amplifier. The loud speaker produces an incident sound and when it excites the panel, the transmitted and reflected sounds occur. Sound pressure levels of the transmitted signal through the panel are measured using microphones and they are analyzed and displayed at the dynamic signal analyzer (HP35665A). Through the measurement of sound pressure level, the plane wave is guaranteed below 800 Hz.

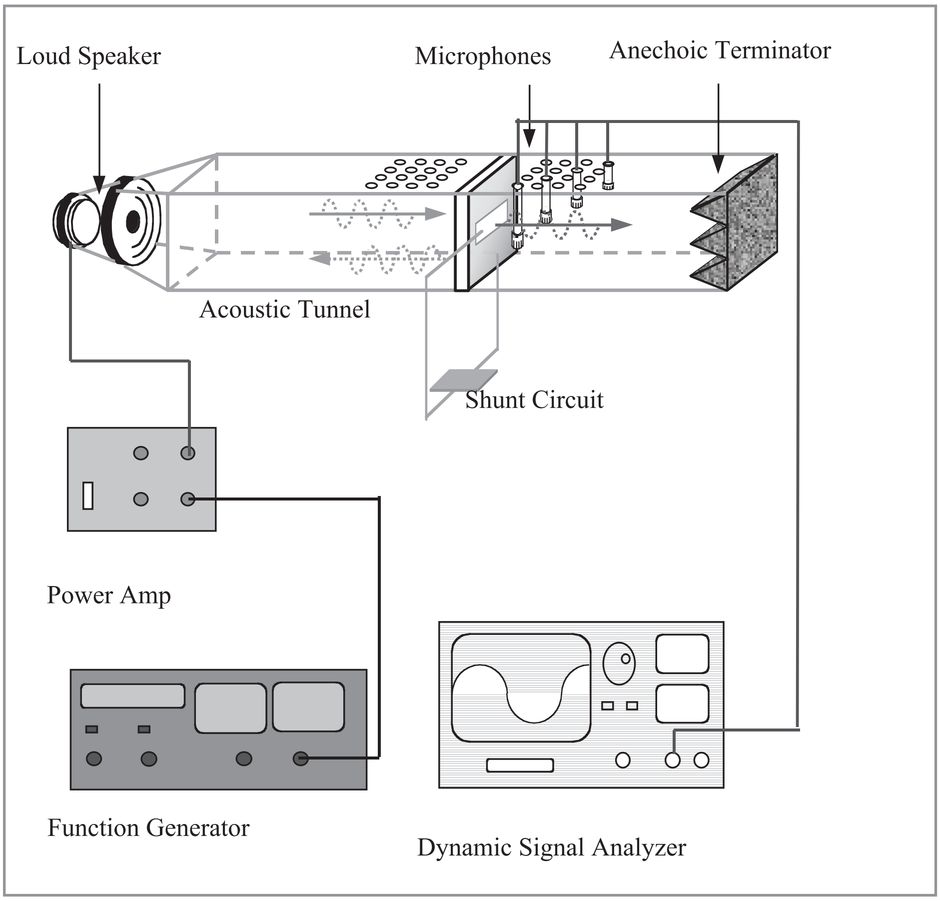
Through the modal analysis of the panel structure, the 1st and 5th modes were known to be 133 Hz and 513 Hz. The location of the piezoceramic patch was chosen to be at the center of panel.

Table I. Van dyke's coefficients (C_0, C_1, L_1, R_1) are found by analyzing the measured admittance, and the optimal parameters (L_1^*, R_1^*, L_1^{block}, C_1^{block}) for multi-mode shunt damping are determined in order to dissipate the maximum power through the load resistor.

	Parameters		Single Mode		Multi mode	
Freq.	**Coeff.**	**Values**	**Simul.**	**Experi.**	**Simul.**	**Experi.**
	C_0 (F)	3.3161e-7	$L_1^*=4.42$	$L_1^*=3.98$	$L_1^*=4.42$	$L_1^*3.98$
1st mode	C1(F)	9.413e-9				
(127.3Hz)	L_1(H)	162.9	$R_1^*=511.02$	$R_1^*=600$	$R_1^*=511.02$	$R_1^*=150$
	R_1(ohm)	9097				
	C_0	3.160e-7	$L_2^*=0.30$	$L_2^*=0.30$	$\tilde{L}_2^*=0.458$	$\tilde{L}_2^*=0.446$
5th mode	C_1	1.161e-8				
(518.1Hz)	L_1	8.421	$R_2^*=125.25$	$R_2^*=100$	$\tilde{R}_2^*=165.9$	$\tilde{R}_2^*=120$
	R_1	644				

INTUITIVE CITING IN HUNTINGDON

In Huntingdon Borough, Pensylvania police officers play it by ear when deciding whom to cite for noise violations. "Our rule of thumb, especially with night calls, is if the responding officer can hear the noise and finds it to be too loud or above what a normal person would find annoying or alarming," said Daniel Varner, borough manager and police chief. Those making too much noise could face fines up to $300, although Varner said officers don't have to write many citations. "We usually just tell people to turn it down," he said. Huntingdon isn't alone. Not all municipalities have noise ordinances, and those that do might not define how loud is too loud. The issue came to light this month when the owner of a teen concert hall in Bedford clashed with Borough Council over the town's noise ordinance. The council has warned owner Kenny Fetterman to keep it down at The NoteWorthy. Fetterman contends that the ordinance, which doesn't specify decibel levels, is too vague. Some municipalities, such as Logan Township in Blair County, have ordinances that state noise levels must be measured in decibels and must be read using a sound level meter. The township's ordinance restricts sound to 55 decibels in residential areas and 62 decibels in industrial areas, with higher levels for construction equipment and industrial machinery. Borough Manager John Montgomery said Bedford's noise ordinance doesn't set decibel limits because the borough doesn't have a decibel reader. Having a more specific ordinance, he said after a borough meeting in June, would mean purchasing a meter, having it certified and employing someone to read it. That's what makes noise ordinances so hard to enforce, said Tom Lang, code enforcement officer for Tyrone Borough. "The main reason we don't have one is because you have to take on a decibel reader for it to be really effective," Lang said. Without one, "you don't have a leg to stand on," said Mary Beth Lake, Member Services Manager for the Pennsylvania League of Cities and Municipalities. "The measurement of noise decibels is an expensive venture," Lake said.



Fligure 4. Schematic diagram of experimental apparatus

5. RESULTS AND DISCUSSIONS

Two experiments were accomplished for the transmitted noise reduction: 1st and 5th modes were tuned separately, and simultaneously. The impedance of piezoelectric smart panel was measured and the parameters for the equivalent impedance model (Van Dyke) were extracted using the PRAP software, for the first and fifth modes, respectively. The second column in Table 1 shows these values.

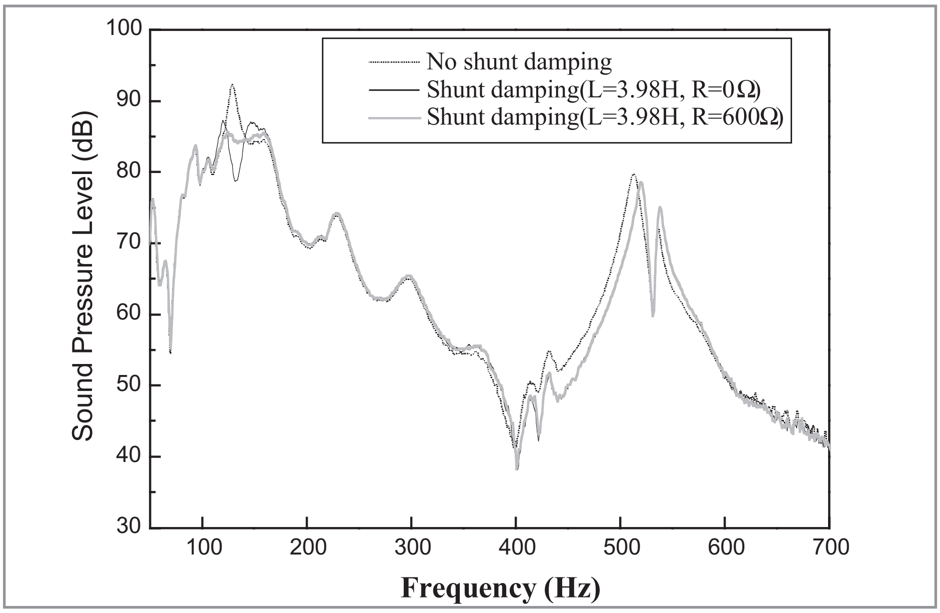


Figure 5. Shunt damping for 1st mode

At first, the piezoelectric shunt damping was tested for the first and fifth modes individually. The third column in Table 1 exhibits the shunt circuit parameters found by the optimization for each mode (Simul.). Due to the presence of uncertainties in the system, the optimally found parameters are necessarily adjusted in the experiment. Thus, the inductance (L_1) and resistance (R_1) were adjusted from the optimal simulation results. The experimental values were also shown in Table 1. The simulation and experimental values shows more close comparison. Figure 5 shows the sound pressure levels near the first resonance. $R = 600\Omega$ is the optimal resistance experimentally found for the resonant shunt. When $R = 0\Omega$ was plotted for a comparison, 7dB reduction of the transmitted sound pressure level was obtained near the first resonance frequency. Figure 6 shows the sound pressure levels near the fifth resonance frequency. At the fifth mode, much more reduction is obtained by 20 dB down since there is much strain at the center of panel, which results in larger electrical energy generation from the piezoelectric patch.

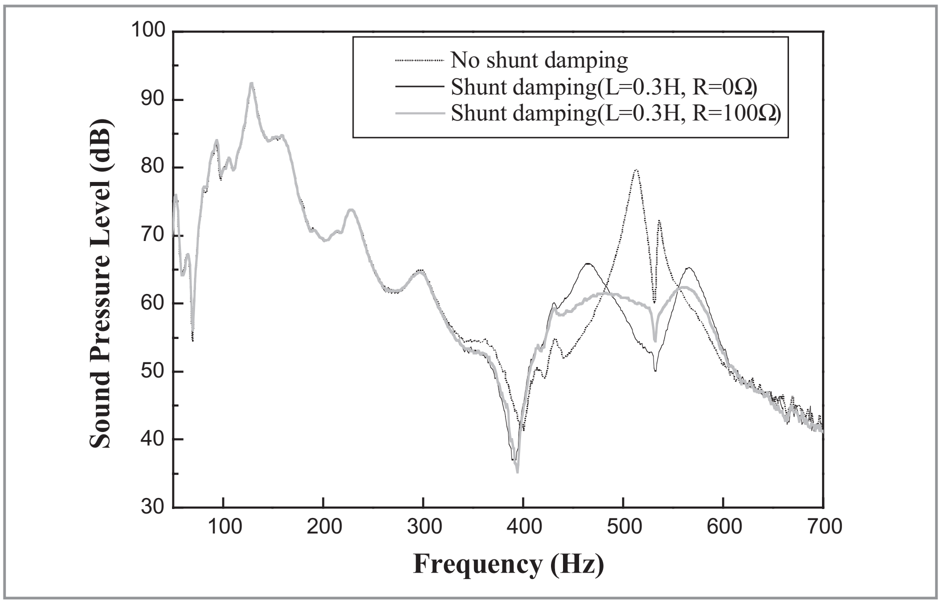


Figure 6. Shunt damping for 5th mode

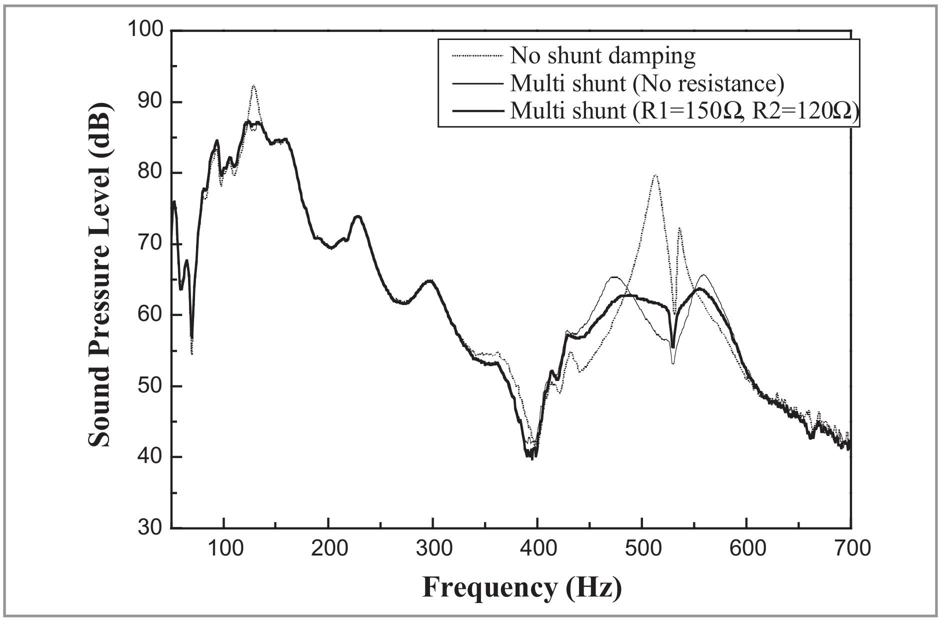


Figure 7. Experimental result for multi-modes shunt damping

Secondly, the experiment for multi-mode shunt damping was performed. By keeping the shunt circuit parameters for the first mode L_1^*, R_1^*, those for the fifth mode were tuned. During the tuning process, the impedance analyzer was employed to measure the inductance and resistance of the circuit directly. The last two columns in Table 1 show the simulation and experimental values. Figure 7 shows the transmitted sound pressure levels when two modes were reduced simultaneously. The sound pressure levels in two resonance modes were reduced by 6dB and 20dB, respectively. The reduction level at the first mode is 1 dB less than the individual tuning result. This is due to a slight leakage of the current flowing into the blocking branch.

When this multi-mode shunt technology is combined with the use of several piezoelectric patches, the application for large-scale structures will be possible for broadband noise reduction. Also, the use of a coil inductor for the circuit may be attractive for real applications since coil inductors are compact and do not require any external power.

6. CONCLUSIONS

Multi-mode shunt damping of piezoelectric smart panel was studied for the noise reduction of the panel. A single piezoceramic patch was bonded on a host panel and a shunt circuit was connected to the patch to accomplish multi-mode shunt damping. As a tuning method, the maximum dissipated energy method in conjunction with the electrical impedance model was adopted. In implementing the shunt circuit, a coil inductor was used instead of synthetic inductor, which does not require external power to drive the circuit. The optimal values of shunt parameters were verified by measuring these values of the shunt circuit.

In the single mode tests, 7 dB and 20 dB noise reduction were obtained at the first and fifth resonance modes of the panel, respectively. By implementing the multi-mode shunt damping, 6 dB and 20 dB noise reductions were obtained simultaneously for each mode, which are almost the same as the single-mode test results. When this multi-mode shunt technology is combined with the use of several piezoelectric patches, the application for broadband noise reduction of large scale structures will be possible.

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NZ

New Zealand's Transport Safety Minister Harry Duynhoven has announced that regulations allowing objective car noise tests would come into force during July. Mr Duynhoven said noise-measuring equipment was coming into the country and would soon be available at nine sites around the country. There would also be one travelling machine. Noisy cars could be subjected to a test if they were pulled up by police. Police would "green sticker" offending cars, which would then have to be taken off the road until they passed a test. At the moment cars undergo a subjective test as part of getting a warrant of fitness. Mr Duynhoven said the Government intended amending the law so objective tests could be brought into the warrant of fitness testing regime. Amending the law would also allow the acceptable noise level to be changed.

WHOSE FAULT IS THE ANNOYANCE?

Club DNA, in Regent Street, Rugby was fined £5,000 with £944 costs by Rugby magistrates after admitting breaking the Environment Protection Act. The charge was brought by the council after they received a 'number' of complaints from residents regarding late night noise at the venue. The council's Environmental Health Division has now requested a review of the club's 24 hour licence. The council claimed that complaints over the venue's noise had continued over 'months', and despite efforts from the police and the council, the club's management had failed to address the problem. However, manager Den Hau said: "The police themselves have told us it's the council's fault. They give out grants for people to live above shops in this area. If they want to encourage people to live in the town, they should give them sound proofing."