Smart panel technology for broadband noise reduction

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The possibility of a broadband noise reduction by piezoelectric smart panels is demonstrated. A smart panel is basically a plate structure on which piezoelectric patches with electrical shunt circuits are mounted and sound absorbing material is bonded on the surface of the structure. Sound absorbing material can absorb the sound transmitted at the mid frequency region effectively while the use of piezoelectric shunt damping can reduce the transmission at resonance frequencies of the panel structure. To be able to reduce the sound transmission at low panel resonance frequencies, piezoelectric damping is adopted. A resonant shunt circuit for piezoelectric shunt damping is composed of resistor and inductor in series, and they are determined by maximizing the dissipated energy through the circuit.

The transmitted noise reduction performance of smart panels was tested in an acoustic tunnel. Sound absorbing material and air gap reduces the sound transmitted at the mid-frequency region effectively while the use of piezoelectric shunt damping works at the low frequency region. As a result, a remarkable noise reduction of 9–15dB was achieved in broadband frequency. Double panel exhibits better noise reduction than other panels. This approach was also applied to the structural acoustic problem of turbulent boundary layer (TBL) induced sound radiated from a panel, and the possibility of TBL noise reduction was demonstrated. The hybrid approach of smart panels is a promising technology for noise reduction over broad frequency band.

1. Introduction

Noise reduction of vibrating structures is a crucial issue in many engineering systems including automobiles, airplanes, ships and buildings. In controlling noise, there are two distinct approaches: passive and active methods. Passive methods are based on the design of material properties or shapes of the structures so as to minimize the radiated noise. Exploiting sound absorbing layers in the structures is a good example of passive noise control [1]. However, the passive approach requires an increasing amount of material for effective noise reduction at low frequencies. Smart materials or structures have emerged as promising active techniques to reduce the radiated sound field. In such structures, piezoelectric materials are widely used as active devices on the structures. Successful noise reductions have been obtained by using piezoelectric sensors and actuators such that active structural acoustic control has been achieved [2]. However, this approach is not feasible at high frequencies due to the increased complexity of the controller which has to take into account many radiating modes of the structure. Moving away from the limited frequency band of noise control, it is natural to combine passive and active approaches. It is based on the idea of utilizing a passive effect at high frequencies and an active effect at low frequencies. An example of this idea is smart foam that uses polyurethane foam for high frequency noise reduction and PVDF actuators with a controller for low frequency noise suppression [3]. Kim et al. proposed combining the piezoelectric smart structure technology with passive sound absorbing material to suppress the transmitted noise of smart panels over broad frequency band [4]. Instead of using a complicated controller for active structural acoustic control for low frequencies, the piezoelectric smart panel featuring piezoelectric shunt damping and passive sound absorbing material has been proposed [5].

Passive damping schemes using piezoelectric devices were discussed by Forward and have been experimentally demonstrated in an optical system [6]. A fundamental scheme of piezo-damping is the fact that vibration suppression can be achieved by using piezoelectric materials with a passive electric network that has either inductor or resistor or both, namely a shunt circuit [7]. The use of piezo-damping at selectively chosen modes of a structure would be very effective in reducing the structure-borne noise.

The key of piezoelectric shunt damping is to tune the shunting circuit such that the dissipated energy is maximized. The optimal tuning method has been widely used [7]. This is to tune the electrical resonance of a shunting circuit to structural resonance in a manner analogous to a mechanical vibration absorber. However, there are some difficulties when this approach is applied to vibration suppression for multiple modes because individually tuned circuits can interfere with each other. Also, the modelling of piezoelectric smart structures in the mechanical domain is too complicated to optimally design the shunting parameters. Another method for passive piezoelectric shunt damping of multiple vibration modes has been reported using a single piezoelectric transducer and employing a blocking circuit in series with each parallel shunt circuit [8,9]. However, since this method requires too many inductors, implementation of the blocking and shunt circuits is not so easy. A method has been presented for implementing simulated impedance required for effective shunt damping of a resonant structure [10]. The arbitrary impedance has also created the opportunity for more advanced passive controllers that adapt to structural variations, i.e. adaptive controllers.

To cope with difficulties in conventional tuning methods, a new tuning method for passive piezoelectric damping, which is based on the electrical impedance model and maximum dissipated energy, has been proposed and its validity has been investigated [11]. The proposed method uses an electrical impedance model of which the coefficients of the model are found from the measured impedance data. In the tuning process, the optimal shunt parameters are found for maximizing the dissipated energy at the shunt circuit. Since this method is based on the measured electrical impedance data, it can be easily applied to arbitrary shape or size of piezoelectric structures once the electrical impedance is measurable. It is also applicable to multi-mode piezoelectric damping.

Several concepts of smart panels are proposed based upon a combination of sound absorbing material and piezoelectric shunt damping. Their transmitted noise is tested in an acoustic tunnel, and the smart panel idea is applied to the structural acoustic problem of turbulent boundary layer (TBL) induced sound at an aircraft fuselage panel.

2. The concept of Smart Panels

Figure 1 illustrates the concept of smart panels. The proposed smart panel is basically a plate structure on which the piezoelectric patch with a shunt circuit is connected (single panel). In addition, the use of sound-absorbing material can enhance the noise reduction in the mid- and high frequency regions (single panel with absorbing material). The piezoelectric patch converts mechanical energy into electrical energy, and the connected shunt circuit effectively dissipates out the electrical energy as heat energy so as to reduce the noise at the low frequency region. To verify the proposed concept, two smart panels – single and single with absorbing material panels are manufactured. 300mm x 300mm x 0.8mm square aluminum plate is used for the host structure and 15mm thick polyurethane foam is glued on the plate. A 40 mm x 80 mm x 0.8 mm piezoceramic patch (PZT-5) is located at the centre of the plate to take into account the first and second symmetric modes. An electronic shunt circuit composed of a resistor and inductor in series is connected to the piezoceramic patch for resonant shunt.

3. Piezoelectric shunt damping

Piezoelectric damping is an energy dissipation mechanism. Open circuited piezoelectric patches store some portion of induced mechanical strain energy as electrical energy, and when a certain resistor is connected across the electrodes, the stored energy begins to flow through the circuit so as to dissipate the energy as heat. In this connection, an inductor is added to cancel the reactive component of the piezoelectric

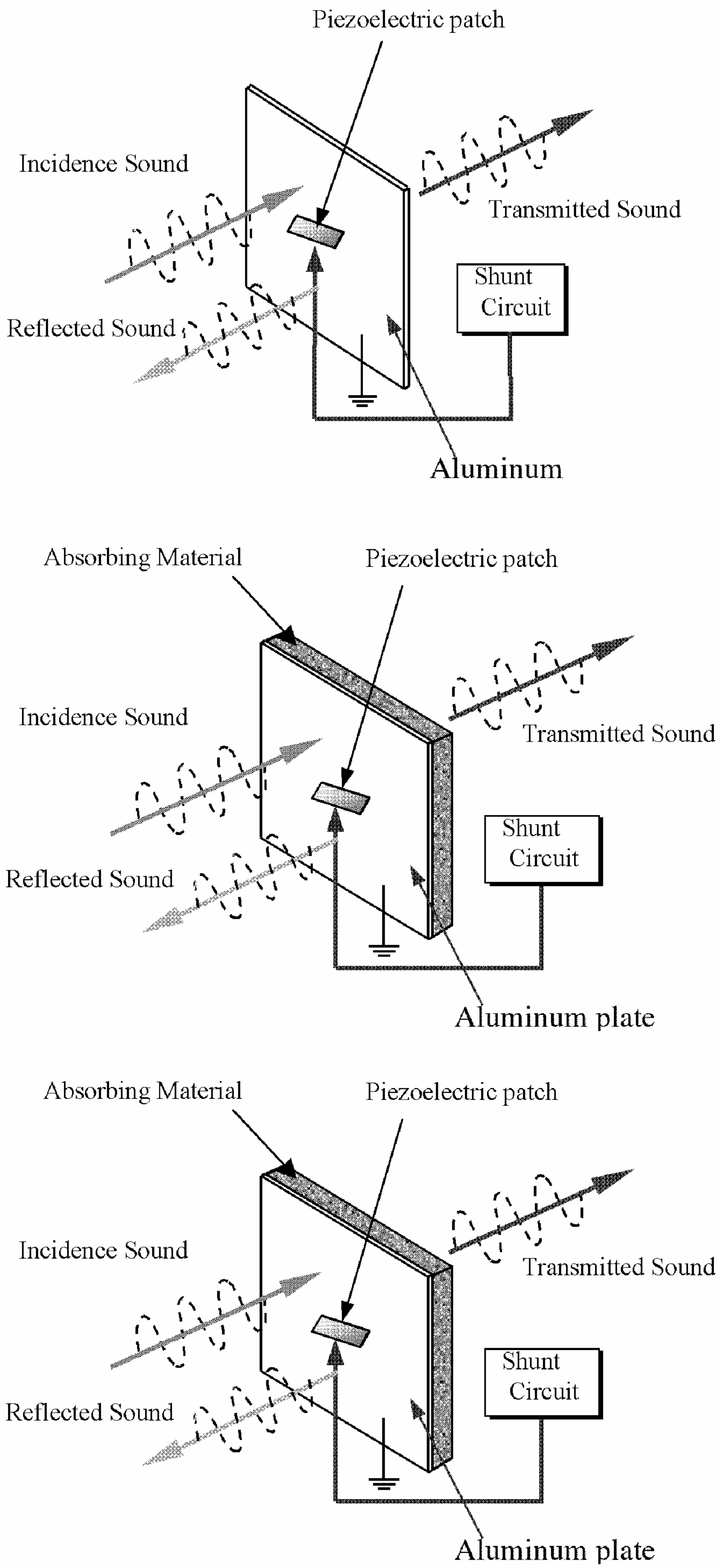

Figure 1. Schematic diagram of smart panels

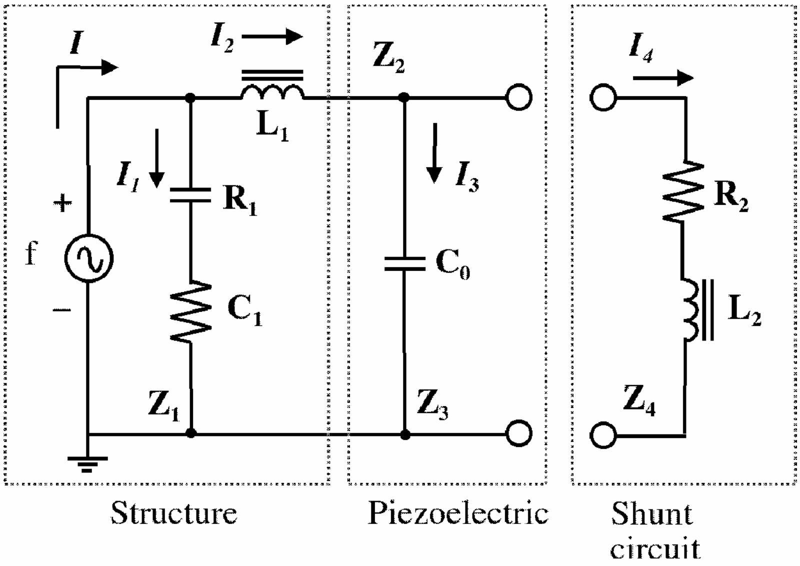

Figure 2. Equivalent electrical circuit

material. The electrical resonance in the shunt circuit with piezoelectric material of which the resonance frequency corresponds to that of the mechanical system, helps more charge flow through an adequately chosen resistor. This is the so called resonant shunt. Since the maximum energy dissipation does not happen at the resonance frequency of the system, the choice of the optimal inductance and resistance is the key. In this paper, the new parameter tuning method based on an electrical impedance model and the maximum dissipation energy criterion is adopted [11].

Piezoelectric materials can be approximately represented as equivalent electric circuits at resonance. Generally, resonant circuit models are represented in terms of electrical characteristics such as inherent capacitance (C_0), and mechanical characteristics such as mass, damping and stiffness coefficients (L_1, R_1, C_1), namely the Van Dyke model. Figure 2 represents the impedance model of a structure on which piezoelectric patch is bonded. Since the diagram is an impedance representation, the impedance values between the nodes can be written as,

$$
\begin{aligned}
Z_1 &= \frac{C_1}{j\omega} + R_1 \\
Z_2 &= j\omega L_1 \\
Z_3 &= \frac{1}{j\omega C_0} \\
Z_4 &= j\omega L_2 + R_2
\end{aligned}
\tag{1}
$$

Here, C_1, R_1, L_1 represent the inverse of stiffness, damping and mass of the structure, respectively. Using Kirchhoff's voltage and current laws, the total electrical impedance and the current at each branch can be written as

$$
Z = \frac{Z_1\left[Z_2 + \frac{Z_3 Z_4}{Z_3 + Z_4}\right]}{Z_1 + \left[Z_2 + \frac{Z_3 Z_4}{Z_3 + Z_4}\right]} \tag{2}
$$

$$
I_1 = \frac{Z}{Z_1} I,\ I_2 = \left(1 - \frac{Z}{Z_1}\right) I,\ I_3 = \frac{Z_4 (Z_1 - Z)}{Z_1 (Z_3 + Z_4)} I,\ I_4 = \frac{Z_3 (Z_1 - Z)}{Z_1 (Z_3 + Z_4)} I \tag{3}
$$

The transfer function between the current input generated by the piezoelectric element and the current passing through the shunt circuit can be written as

$$\frac{I_2}{I} = 1 - \frac{Z}{Z_1}. \tag{4}$$

This transfer function is analogous to the transfer function of a mechanical vibration absorber [7]. To use the proposed electrical impedance model of piezoelectric structures, the coefficients of the Van Dyke model should be determined. This can be solved by measuring the electrical impedance of piezoelectric patches bonded on the structure directly. When electrical impedance is measured using the impedance analyzer (HP 4192A), the coefficients of the Van Dyke or complex circuit model can be determined by using PRAP (piezoelectric resonance analysis program) software [12].

Parameter tuning of shunt circuit is essential to maximize the piezoelectric damping performance. For the resonant shunt, the optimal inductance should be determined to coincide with the resonant frequency of the shunt circuit of the piezoelectric structure. The optimal resistance of the shunt circuit should also be found for maximizing the dissipated energy. Instead of tuning the transfer function geometrically as used in conventional tuning method, the new parameter tuning method associated with maximum dissipated energy is adopted. From the equivalent electrical model shown in Figure 2, the induced energy in the structure associated with external excitation is

$$P_{IN} = \frac{1}{2}\left|V \cdot I\right| = \frac{1}{2}\left|(Z \cdot I)\cdot I^*\right| = \frac{1}{2}|Z||I|^2. \tag{5}$$

The dissipated energy at the shunt circuit can be written

$$P_D = \frac{1}{2}\mathrm{Re}\left[(Z_4 \cdot I_4)\cdot I_4^*\right] = \frac{1}{2}\mathrm{Re}\left[\frac{Z_3 \cdot Z_4}{(Z_3 + Z_4)} \cdot \frac{(Z_1 - Z)}{Z_1}\right]|I|^2. \tag{6}$$

In the tuning process, the ratio of the dissipated energy to the input energy should be maximized by optimally changing the shunting parameters,

$$\max_{L_2, R_2} J = \frac{P_D}{P_{IN}} = \mathrm{Re}\left[\frac{Z_3 \cdot Z_4}{(Z_3 + Z_4)} \cdot \frac{(Z_1 - Z)}{Z_1}\right] \Big/ |Z| \tag{7}$$

Since the ratio J varies with respect to the frequency, the objective function in optimization is taken as the averaged J at a certain frequency band near the targeted resonance frequency.

4. Acoustic test for Smart Panels

To test the noise reduction performance of smart panels, the transmission measurement from low to high frequencies should be available. For most panel materials the transmission loss has been measured under strict control. The experimental procedure most often used follows the ASTM standard E 90 [13]. Since this test facility is too expensive a simple acoustic tunnel is used instead. The tunnel is a square tube of 300mm x 300mm and 4m long (Figure 3). It is divided into two sections – upper and lower sections of equal length. A loudspeaker is attached at the end of the upper section and an anechoic termination is made with wedges installed at the other end of the lower section. A specially designed flange is provided where two sections meet such

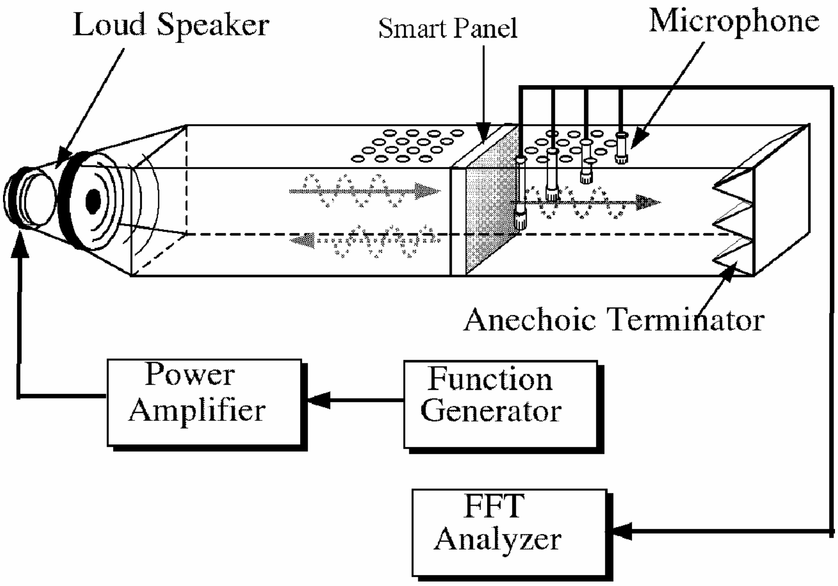

Figure 3. Experimental apparatus

that smart panels can be mounted in between. The four edges of the smart panel are clamped using bolts and two sections are tightly connected. The tunnel is made of 4.5mm thick steel plates and 6 mm thick polyurethane foam coats the inside of the tunnel. Sixteen holes are made on lower and upper sections of the tunnel to measure the sound pressures across the cross section of the tunnel at four locations. From the repeated measurement of sound pressure distribution at a cross section, the pressure distribution is found to be nearly plane below 800 Hz [5]. In the transmission measurement, four microphones along the diagonal of the lower section are used. According to the duct noise measurement standard, the average value of four microphone pressures is used to calculate the transmission power. The same idea is adopted to find out the transmission power. The cutoff frequency of the anechoic termination is 60 Hz.

4.1. Shunt parameter tuning

As shown in Figure 1, a 300mm x 300mm x 0.8mm square aluminum plate is used for the host structure and a 40 mm x 80 mm x 0.8 mm piezoceramic patch (PZT-5) is bonded at the centre of the plate, a single panel. 15-mm thick polyurethane foam is bonded on one side of the single panel to enhance noise reduction performance at mid and high frequency regions. Impedance curves of a single panel with and without sound-absorbing material were measured by the HP4192A impedance analyzer (Figure 4). PRAP software was used to determine the parameters of the Van Dyke equivalent model, and the optimal parameters of the R-L shunt circuit were obtained by using the dissipated energy method (Table 1).

To construct the optimal inductance, a synthetic inductor and a coil inductor were used. The synthetic inductor is lightweight and can generate various inductance values, but it has also a resistance proportional to the inductance which is not desirable for designing the optimal resistance in the shunt circuit. The inductance value of the synthetic inductor was measured at the resonance frequency by using the impedance analyzer (Table 1). Similar values for the shunt circuit parameters were observed. However, the use of a synthetic inductor requires external power to drive OP amps of the circuit,

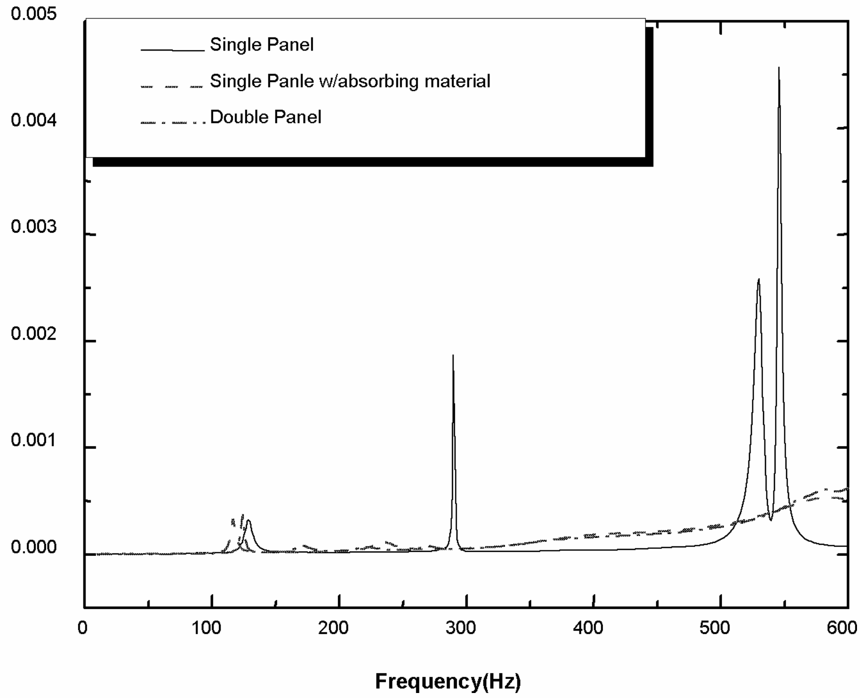

Figure 4. Measured impedance of smart panels

which is an obstacle for commercial applications. Furthermore, the synthetic inductor circuits can interfere with each other. Thus, a coil inductor is used instead of the synthetic inductor. The use of a coil inductor has many advantages – cheap, less interference with other components, no external power requirement, and easy to install. Also to implement an independent system of piezoelectric smart panels, the coil inductor can be easily integrated into the panels without any external power.

4.2. Acoustic tunnel test

To investigate the performance of transmitted noise reduction, three smart panels were tested in the acoustic tunnel. Ranges of the selected low frequencies for shunt damping were from 100 Hz to 143 Hz for the single panel, from 100 Hz to 160 Hz for the single panel with absorbing material and from 100 Hz to 164 Hz for the double panel. Before testing the smart panel with piezoelectric shunt damping, sound transmission characteristics of the host plate and the plate with sound absorbing material were tested (Figure 5). For the host plate, the first and second resonance frequencies are 87 Hz and 296 Hz, respectively. When the absorbing material is bonded on the plate, the first and second modes are shifted to 86

Table I. Optimal and measured parameters of the shunt circuit

	Freq. (Hz)	Parameter	Van Dyke	Measured
Single panel	128Hz	R2(Ω)	1890	1523
		L2(H)	2.25	2.34
Single panel with absorbent material	116Hz	R2(Ω)	991	693
		L2(H)	3.1	2.98
Double panel	123Hz	R2(Ω)	1190	1596
		L2(H)	2.4	2.45

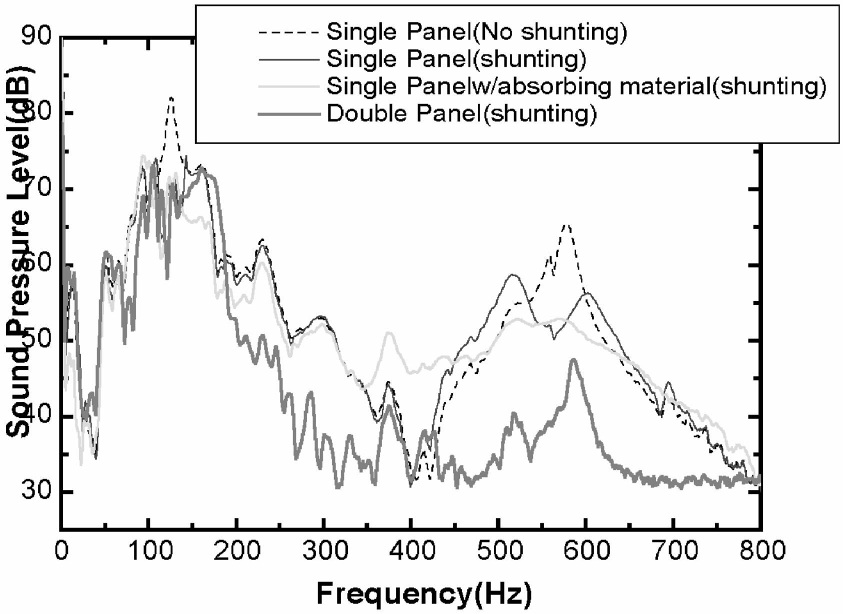

Figure 5. Transmitted SPL for smart panels

Hz and 226 Hz, respectively due to the added mass effect. Through the test of sound characteristic, it is evident that the sound reduction in a mid-frequency region is obtained by adding absorbing material except the first resonance frequency.

Figure 5 shows the transmitted sound pressure level (SPL) of three panels. In the single panel, 9 dB noise reduction was achieved at the frequency range of 100 Hz to 143 Hz. Also when the shunt damping using the remaining one PZT was tuned at 590 Hz, the transmitted noise was decreased by 14 dB. In the single panel with absorbing material, the SPL at mid-frequency range near 590 Hz was decreased because the sound absorbing material works at mid frequency range. In the double panel case, the transmitted noise was drastically reduced at mid frequency range due to the presence of air gap. By applying shunt damping at low frequency range, nearly 9 dB reduction of the transmitted SPL was achieved. The noise reduction in the mid frequency range was evidently obtained by the use of absorbing material and air gap. The noise reduction level of the panels can be more improved by optimizing the size and location of the piezoelectric patches.

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 means increasing the weight of the system. Thus, the multi-mode shunt damping with 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 research, a blocking circuit is adopted to construct a multi-mode shunt circuit (Figure 6). The blocking circuit blocks the current flow passing through the branch at the target frequency. Before determining parameters for multi-mode shunt circuit, single-mode shunt parameters should be known. These values are employed from the previous tuning process for single-mode shunt damping. As shown in Figure 6, two resonance modes are investigated in this study. Tuned parameters for the first mode are kept in the tuning process for multi-mode shunt damping, and the blocking circuit is designed for the 1st mode by satisfying the next resonance equation,

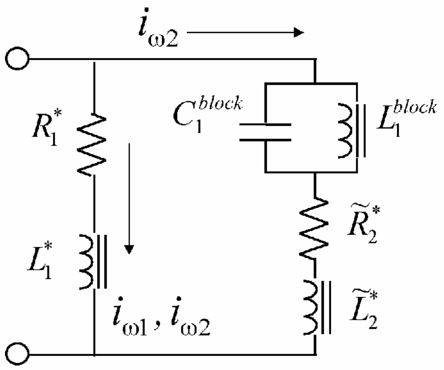

Figure 6. Shunt circuit for multi-mode shunt damping

$$\omega_1^2 = \frac{1}{L_1^{block} \cdot C_1^{block}} . \qquad (8)$$

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. Figure 7 shows the transmitted SPLs when two modes were reduced simultaneously. SPLs at two resonance modes were reduced by 6 dB and 20 dB, respectively, which are almost the same as the individual tuning results.

5. Application for TBL noise reduction

TBL induced noise and jet noise are the dominant sources of interior noise in high sub-sonic and supersonic aircraft. These sources are broadband in nature, and much more difficult to control than narrowband. In addition, TBL noise is spatially and temporally incoherent, thus limiting the use of TBL pressure measurements as reference signals for feedforward control. Therefore, the piezoelectric shunt damping approach was applied to this problem of turbulent boundary layer induced noise radiated from a panel.

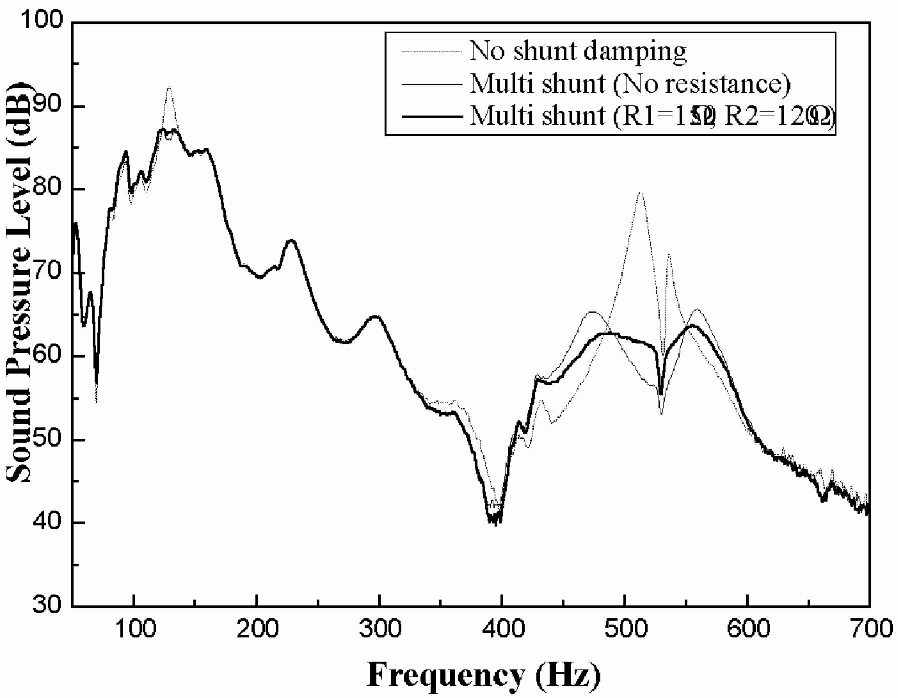

Figure 7. Transmitted SPL for smart panels (multi-mode)

In order to simulate aircraft construction a tensioned panel assembly was used. The aluminum test panel as shown in Figure 8 is 1.6 mm thick, with dimensions of 150 cm in the flow direction and 50 cm in the cross flow direction [14]. The test panel had two vertical frames and one horizontal stringer, which partitioned the panel into 6 frame bays each with dimensions 50 cm x 25 cm. The panel was tensioned in the cross flow direction only to simulate the hoop stress due to flight pressurization at 40,000 ft. On the lower centre bay, three piezoelectric patches (150 mm x 100 mm x 0.4 mm) were bonded. The panel was tested in the Structural Acoustic Flow Apparatus (SAFA) at NASA Langley Research Centre. SAFA is a low speed wind tunnel with a test section of 50 cm x 50 cm. The tensioned panel assembly replaced the side wall of the tunnel such that air flowed along one surface of the panel. The centre PZT patch on the panel was used for the piezoelectric shunt damping. The tuning process used before was adopted again. The time-domain response of four accelerometers centred around the PZT patch were summed in order to estimate the volumetric motion of the panel. At low frequencies, sound radiation from the panel is approximately proportional to volumetric motion of the panel. Figure 9 shows the acceleration result at 260 Hz for a tunnel flow speed of Mach 0.1. The dotted line is when the shunt circuit is off and the solid line represents "on". By turning on the shunt circuit, the acceleration level was reduced by 7 dB. The simplicity of this approach is appealing for the aircraft noise control problem, although the sensitivity of the shunt circuit to changes in the structure due to aircraft pressurization must be addressed.

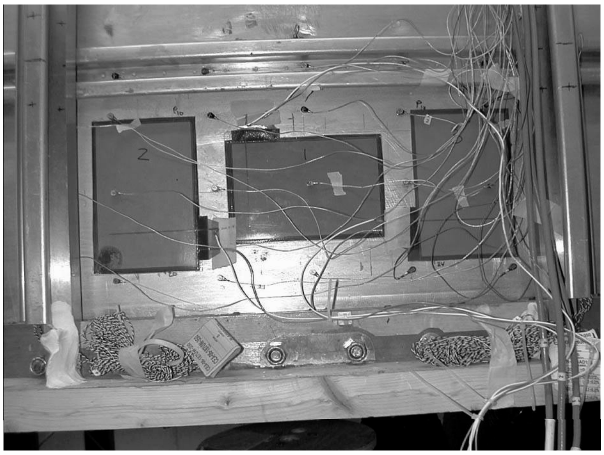

Figure 8. Photograph of test panel for TBL induced noise

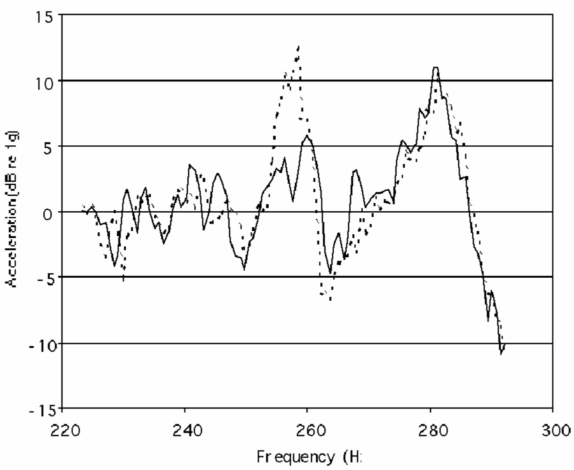

Figure 9. Shunt damping result for TBL noise

6. Conclusions

To reduce transmission noise over a broad frequency band, the concept of smart panels featuring a piezoelectric shunt circuit and sound absorbing material was experimentally verified. It is based on the idea of utilizing a passive effect at mid and high frequencies and a piezoelectric damping effect at low frequency. In parameter tuning of piezoelectric shunt circuit, the new parameter tuning method associated with the electrical impedance model and maximum dissipated energy was used. To test the noise reduction performance of smart panels, an acoustic tunnel was designed such that it can measure the transmission and reflection of panels.

When the single and double smart panels along with and without sound absorbing material were tested in the acoustic tunnel, 9dB and 15dB of transmission noise reduction were observed. Multi-mode shunt damping of piezoelectric smart panel was studied for the noise reduction of the panel. By implementing the multi-mode shunt damping with a single piezoelectric patch, 6 dB and 20 dB noise reductions were obtained simultaneously for each mode, which are almost the same noise reductions as the single-mode test results. This approach was also applied to the structural acoustic problem of turbulent boundary layer (TBL) induced sound radiated from a panel to demonstrate its possibility for noise reduction.

This approach can be easily applied to arbitrary structures on which piezoelectric patches are bonded and multi-mode damping with single piezoelectric patch is possible. The hybrid approach combining the piezoelectric shunt damping and sound absorbing material is a promising technique for noise reduction over a broad frequency band. The merits of this approach are to tune the damping at a specific frequency band and to be able to apply it to arbitrary shaped structures, for example, enclosures, sound barriers and interior trim panels for aircraft, automobiles, buildings, ships, etc.

Acknowledgement

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Helicopters

Some residents of Geunhwa-dong, Chuncheon, Gangwon province, sued the Korean government yesterday for 420 million won ($352.000), which they claim as compensation for damage to their hearing that they say was caused by helicopter noise form Camp Page, a U.S. military base. Lee Seung-hun and 41 others submitted their claim to the Chuncheon District Court. They said they based their suit on charges filed by citizens living near the Maehyang-ri U.S. bombing range and the Gunsan U.S. military base. The plaintiffs claim that helicopter flights in and out of Camp Page since 1958, when it was established, not only impaired their hearing, but also caused chronic anxiety. They state that noise, dust and vibration disturbed students studies and disturbed television broadcasts. They asked 10 million won per person.

noise notes

noise notes

Quiet jets?

Noise created by the increasing number of aircraft flying over residential areas could be permanently eliminated by a new acoustic control technique, NASA claims. A new system developed by Dr Carl Gerhold, a senior researcher at NASA's Langley Research Centre, is said to reduce or even cancel sound generated during take-off and landing. 'The next generation of advanced turbo passenger jets will be propelled using an engine-driven fan rather than providing power through the engine directly,' said Gerhold. 'This has advantages for fuel economy and will slightly improve noise control, but to a large extent engine noise will be replaced by fan noise.' While the interior of the engine duct can be insulated to damp the amount of noise produced, this adds weight to the aircraft, affecting its fuel economy. With the new system a number of speakers are placed around the engine's fan duct. These measure the tone of the noise produced and fire back sound of the same tone, shape and power but out of phase with the oncoming waves. This cancels them out. Unlike previous acoustic control devices which have concentrated on reducing noise at points outside the fan unit, microphone sensors are placed at a number of locations around the fan duct. According to the developers, because this reduces the sound at source it automatically reduces sound transmitted outside, whereas eliminating noise at one point may simply shift the problem to another area.