VIBRO-ACOUSTIC ANALYSIS, RESPONSE MEASUREMENTS AND CONTROL OF AIRCRAFT PANELS

S. Raja*,#, C.N. Sathyanarayana*, D. Dwarakanathan*, N. Chandra*,
B. Balakrishnan*, V. Sudha*, S. Vedaprakash* and K.B. Prasanna*

Abstract

Finite Element based vibro-acoustic modelling and analysis procedures are developed for aircraft panels using commercially available MSC-NASTRAN in the low frequency segment (<250 Hz). A modal strain energy based approach is followed to introduce the Constrained Layer Damping (CLD) at optimally selected locations. Subsequently, a vibro-acoustic test facility has been designed and commissioned to test the aircraft panels with active-passive noise control solutions. A good correlation is observed between numerical simulation of CLD and experiment on an aluminium panel. Further, a two channel active structural acoustic control experiment is conducted and the use of smart structure technology for noise attenuation through structural vibration control has been demonstrated. Thus, the importance of active-passive control solutions for fuselage cabin noise reduction is highlighted.

***Key words**: Sound Pressure Level (SPL), Fluid-Structure Interaction, Active Structural Acoustic Control, Constrained Layer Damping (CLD), Piezoelectric Actuator, Macro Fiber Composite (MFC), Ground Vibration Test (GVT)*

Introduction

Vibro-acoustic response control in a fuselage (cabin) of transport aircraft can be achieved by active, passive, and semi-active methods. Active control technologies for vibration (AVC) involve structural actuators and sensors with either feed forward or feedback control strategies to counteract the disturbances through induced forces. On the other hand active noise control (ANC) concept employs speakers and microphones to produce an out-of-phase signal to electronically cancel the disturbances. In contrast to these active technologies, the conventional passive control approaches for airborne and structure borne noises, include absorbers, barriers, dampers etc. Interestingly, both active and passive techniques can be tailored to device semi-active methods (ER and MR fluids, ACLD) to improve the damping and stiffness of the vibrating system. Indeed the full scale implementation of active and semi-active methods has been attempted in the cabin interior of different aircrafts in recent years [1]. Aircraft industries nevertheless are looking for advanced active control technologies besides considering passive solutions through insulation blankets, primary insulation (CLD), flexure hinges etc.

Grewal, et al. (2000) have developed active structural acoustic control technique to reduce the propeller induced noise and vibration in the passenger cabin of the de Havilland Dash-8 aircraft [2]. Piezoceramic elements as structural actuators and accelerometers as sensors have been used in the velocity feedback control to achieve a noise attenuation of 28 dB in the interior, and fuselage vibration reduction of 16 dB.

Paolo (2002) has reviewed various sources of noise in aerospace vehicles such as airborne, structure borne and also discussed different passive, active noise/vibration control approaches [3]. Mohan (2003) has reviewed the passive damping based noise control solutions through viscoelastic materials for automobiles and commercial airplanes [4]. Concepts such as special damped laminates and spray paints are discussed, addressing issues related to mass production of such technologies. Indranil and Ron (2004) have reported the numerical modelling scheme using AUTOSEA2® for the hawker aircraft, where both airborne noise, structure borne noise and environmental control system noise are considered as inputs to compute the vibro-acoustic responses [5]. A noise transfer analysis has been performed to identify the dominant noise sources and their transmission paths.

---

* Structural Technologies Division, National Aerospace Laboratories, Kodihalli, Post Box No. 1779, Bangalore-560 017, India, #Email : raja@nal.res.in

Michel and Lars (2007) have proposed a concurrent multi-disciplinary design procedure, considering mechanical, acoustical and thermal models for optimally reducing the weight of stiffened and unstiffened simplified fuselage structures [6]. Cotoni et al. (2007) have developed improved modelling schemes for the prediction of vibro-acoustic response at mid and high frequencies of commercial aircraft structures [7]. As an illustration, the actual section of Boeing 737 aircraft with trimmed sidewalls, stowage bins and connected floor structure has been chosen and the transmission of vibration energy through various sub-systems are examined using hybrid FE-SEA (Statistical Energy Analysis) method. Kamal et al. (2008) have proposed different design strategies on heterogeneous (HG) blanket for providing passive control solutions in the low frequency segment to have a quite interior in a aircraft cabin. These HG blankets consider poro-elastic media with small-embedded masses, which act as a distributed spring-mass damping. The literatures review shows that commendable works have been carried out in the areas of vibration-noise predictions and its associated control methods. In different parts of the world, scientists/ researchers/engineers are developing new modelling methodologies, active-passive solutions with new materials and innovations to build transport aircraft, which will have utmost calm and a quite interior. CSIR-NAL has been developing the regional transport aircraft (RTA 70), which may be propeller driven. In order to ensure, acoustically acceptable and a quite environment in the interior of the fuselage, the following approaches have been planned.

- Develop modelling techniques to compute the vibro-acoustic responses in the low, mid and high frequency segments
- Develop/apply passive noise control solutions using CLD, blankets and Tuned Vibration Absorbers (TVA)
- Develop active acoustic control solutions for the critical fuselage segment (near propeller plane) as an add on system, to provide comfort for the passengers during the critical flight manoeuvre

Besides these vibration control measures as noise reduction schemes, further Active Noise Control (ANC) technique has been considered to develop an integrated technology as a total solution for RTA 70.

In the present study, the following issues are addressed.

- A modelling scheme is proposed for computing vibro-acoustic response in the low frequency segment, where structure borne noise is predominant.
- As a passive solution to the fuselage panel, use of CLD is proposed.
- Smart structure based active structural acoustic control technique has been developed and successfully demonstrated through experiments.

And finally conclusions are drawn from the conducted numerical and experimental studies.

Design and Development of Vibro-Acoustic Test Facility

In the present study both vibro-acoustic modelling and experimental measurements are dealt in the low frequency segment (<200 Hz). The structure borne noise is predominantly addressed in this frequency bandwidth. Vibro-acoustic experiment is usually conducted for the following purposes.

- To estimate the sound transmission in terms of sound pressure level
- To compute the sound absorption capability of the structure/material

For the estimation of sound transmission from outside to inside on the aircraft panels, a vibro-acoustic tunnel is designed. Fig.1 shows the side view of the tunnel and its dimension. The structure-acoustic test facility consists of two chambers, namely a source chamber and a receiver chamber. In the source chamber, a speaker (sound source) is positioned, using which the low frequency noise signal has been generated. The complete source chamber is placed on a trolley, so that to facilitate its easy movement for fixing the test panel onto the receiver chamber.

The source chamber is made out of thick ply wood and its inner periphery is insulated with noise absorbing material, namely felt to minimize reflection and as well as radiation effects, besides other disturbance entering from external source. The receiver is cubical in shape ($0.68 \times 0.6 \times 0.6 \text{ m}^3$) and is constructed of steel frames and aluminium sheets (3 mm thick). The inner surface of the receiver is insulated with felt material to minimize the acoustic interference from the sidewalls. The test panel is kept between the source and receiver, through which the incident wave is allowed to be transmitted onto the acoustic cavity of the receiver. Three microphones are placed in the source chamber and two are kept in the receiver chamber at regular intervals. The sound transmitted through the acoustic cavity in the source to receiver, across the test specimen is measured by microphones.

Vibro-Acoustic Analysis of Aircraft Panel

The approach used in this analysis is known as *Pressure Method*. In this scheme, the fluid is modelled with the existing three-dimensional elements such as CHEXA, CPENTA, and CTETRA. And these elements assume the properties of irrotational and compressible fluids, which are suitable for the acoustic analysis. MSC/NASTRAN supports structure-fluid analyses, which include general acoustics (coupled structure-fluid method) and cavity acoustics. The boundaries of the cavities are defined either by constraints or structural finite elements, which may define rigid, open, damped, or flexible conditions. In contrast, the interior fluid volume is modelled with three dimensional solid elements, connected through a special set of grid points. As the first step, normal mode analysis is carried out to obtain the natural frequencies of the structure and fluid domain independently using solution 103 and subsequently a coupled fluid-structure (*Vibro-acoustic system*) analysis is performed using the complex Eigen value solution for computing the fluid-structure interaction behaviour (Solution 107). Further, the modal frequency response (Solution 111) is obtained on the coupled vibro-acoustic system to establish the Sound Pressure Level (SPL) due to acoustic loading on the vibrating panel. The acoustic loading is expressed in terms of mechanical energy (Pascal). Since this analysis procedure simplifies the equation of motion in modal domain and computes the response in the uncoupled state, it can be applied to a relatively large model like fuselage.

Numerical Modelling of Viscoelastic Damping and Analysis

The aircraft panel and the constraining layer are modelled by three-dimensional solid elements (HEXA). However, the middle damping layer is idealized by three-dimensional solid elements (HEX / PENT). The material properties (Table-1) of the damping layer are treated as real and constant so that a standard normal-mode analysis (Solution 103) can be carried out. A Modal Strain Energy (MSE) is used to compute the modal loss factor (*Passive damping*) for different elastic modes by the viscoelastic layer. The frequencies of the vibro-acoustic system have been presented in Table-2 along with the experimental values. For the sake of completeness, the first and second coupled mode shapes are presented in Fig.2. The loss factor is defined as:

$$\eta^{(r)} = \sum_{i=1}^{n} \eta_i \frac{E^r_{Si}}{E^r_S}$$

where

$\eta^{(r)}$ = System's modal loss factor at the rth mode

η_i = Material loss factor for CLD material

E^r_{Si} = Average strain energy in the material (CLD) i, when the structure deforms in rth mode

E^r_S = System's total strain energy in the rth mode

The constrained layer damping (CLD) has been introduced through viscoelastic patches onto the aircraft panel, in terms of loss factor. The patches are optimally located (30% of the plate surface area), following the modal strain energy pattern of the fundamental mode (Fig.3). Subsequently, the modal response analysis has been performed to obtain the frequency response with and without

Table-1 : Material Data

Material	Young's Modulus E (MPa)	Density ρ (Kg/m^3)	Poisson's Ratio	Dimensions (m)
Aluminium	70 x 10^3	2700	0.3	0.5x 0.5x 0.001
Viscoelastic*	0.89	999	0.49	0.1 x 0.1 x 0.00038 (each patch)

** 3M Damping foil 2552 (The loss factors are estimated through data sheet supplied by the manufacturer)*

Material	Velocity of Sound (C, m/s)	Density (ρ, kg/m^3)	Dimensions (m)
Air	340	1.25	0.4 x 0.4 x 0.66

Note : Bulk modulus (K) = C^2 x ρ

Table-2 : Vibro-acoustic Analysis and Experiment

Frequencies (Hz) : Aluminum Coupon + Fluid (Receiver)					
Mode No	1	2	3	4	5
Experiment (Acoustic Input)	57.60	94.23	109.0	154.20	167.90
Experiment (Mechanical Input)	51.70	89.80	92.70	134.70	160.10

CLD. Fig.4 shows nearly a 5.6 dB reduction with five CLD patches as sound transmission loss due to passive damping. This is further validated with the experiment, conducted on the panel.

Vibro-Acoustic Measurements

Figure 5a,b,c shows the experimental test facility, commissioned at STTD, NAL for vibro-acoustic measurements of aircraft panels. The following instrumentations are used:

- Signal generator (noise) and conditioner
- Microphones, speaker source
- Data acquisition system/analysis software

GVT has been done on the aluminium panel before exciting the specimen by acoustic loading. When the mechanical input is applied, the source chamber has been detached and also the receiver chamber is unclosed. The experimental frequencies are then compared with FEM analysis in Table-2. A band limited random noise (0 to 200 Hz) is generated and has been supplied through a conditioner to the speaker. Thus, the generated low frequency noise is allowed to travel as a plane wave in the source chamber to acoustically excite the plate to produce its vibro-acoustic modes. The sound transmission ability of the plate is captured as the frequency response plot (Fig.6). It is evident from the observed results that around 8 dB reduction is seen from mic 3 to mic 4; which clearly shows the material ability in radiating the sound through vibrating modes.

Noise Control with Constrained Layer Damping (CLD)

Further, a study is made with the constrained layer damping, where the viscoelastic patches are applied on the panel at discrete locations, which are optimally chosen based on the first modal strain energy data.

Figure 7 shows a 13.7dB sound transmission loss, which clearly indicates the damping effect on vibration attenuation that is resulting in interior noise reduction (receiver chamber). It is also interesting to note that the fundamental mode has been the important sound radiator in the tested frequency band (0 to 200 Hz).

In the sound transmission loss with CLD solution, a marginal discrepancy is noticed between the numerical simulation (5.6 dB) and experiment (6.1 dB). This may be due to the following reasons:

- In the numerical analysis, only 0.1 % material damping is assumed.
- Vibro-acoustic loading is applied as an equivalent point force in the numerical simulation, whereas in the experiment a plane incident wave is generated to apply the sound pressure on the surface of the panel.

Nevertheless, the overall SPL reduction (sound transmission loss) has been observed to be nearly close, which ensures a correct modelling of CLD as passive solution for the vibro-acoustic control application.

Active Structural Acoustic Control (ASAC)

In an attempt to develop active-passive vibro-acoustic solution for propeller driven aircraft, the current study has considered active structural acoustic control (ASAC) technique along with passive solutions such as CLD (damping) and insulation blanket.

ASAC is a technique used to control the inputs supplied directly to the structure by means of structural actuators, so that the overall sound radiation through vibrating modes will be reduced [9]. Sound radiation occurs as a result of the continuity of particle displacement at the interface between the structure and the surrounding acoustic (fluid) medium. Indeed ASAC is a typical AVC scheme, where the reference signal is actually an acoustic sound pressure. A feedback control strategy is developed to demonstrate the ASAC technique on the aluminium panel with two MFC actuators and PZT patch sensors (Figs. 8, 9, 10).

A two channel ASAC loops are designed using the Linear Quadratic Gaussian (LQG) algorithm that considers a kalman filter to estimate the full state vector (displacement, velocity). The PZT patch is a strain-rate sensor, which will output displacement. In order to implement a full state linear feedback control for a second order dynamic system, velocity information must be estimated. Table-3 presents the actuators voltages, used in the control experiments. There are two cases attempted as follows:

Case (a): Both actuators are operated in in-phase conditions

Case (b): Both actuators are operated in out-of phase conditions

ASAC experiments are conducted on the panel under the harmonic disturbance of first mode (with harmonics of first mode). Open and closed loop responses are shown in Fig.11. Nearly 8 dB reduction in sound radiation (transmission) is achieved by only controlling the first mode vibration (Case-a).

Table-3 : Actuators Operated in-phase/out-of-phase

Actuator	In-phase (V)	Out-of-phase (V)
*MFC - 1 (ϕ_a)	3.92	3.92
*MFC - 2 (ϕ_a)	3.92	3.92

*Note : Gain (G) = 200, * M8528-P1 : Product of Smart Mateials®, Germany*

Conclusions

Vibro-acoustic modelling and analysis, measurements and control related issues are addressed in the present study. A test facility is designed, fabricated and commissioned to conduct both open and closed loop vibro-acoustic experiments on the aircraft panels. MSC-NASTRAN is used to perform the vibro-acoustic analysis on a aluminium panel in the low frequency segment (<200 Hz). Through the numerical simulation and experiments, it has been shown that a considerable amount of sound transmission reduction is achievable using the constrained layer damping. Further, active structural acoustic control technique is experimentally implemented and a substantial amount of noise reduction is observed (~ 8 dB) with only two MFC actuators. Therefore, it is observed that by properly tailoring the active-passive control techniques, a quite interior may be achieved for the proposed regional transport aircraft (RTA-70).

Acknowledgements

The authors wish to thank Dr. A.R. Upadhya, Director, National Aerospace Laboratories (NAL) for his support, encouragement and technical review of this work at various stages. Authors also like to place their appreciation to Dr. Kota Harinarayana, Raja Ramanna Fellow (DAE), NAL, and Former Director of ADA and Dr. Satish Chandra, Project Director (NCAD) and Head, Structural Technologies Division, NAL, for funding and guiding this project under RTA programme.

References

1. Malcolm J Crocker., Handbook of "Noise and Vibration Control", 2007, John Wiley and Sons, Inc, New Jersey, USA.

2. Grewal, A, Zimick, D. G., Hurtbise, L and Leigh, B., "Active Cabin Noise and Vibration Control for Turboprop Aircraft Using Multiple Piezoelectric Actuators", J. Intelligent Material Systems and Structures, Vol. 11, pp. 438-447, June 2000.

3. Paolo Gardanio., "Review of Active Techniques for Aerospace Vibro-acoustic Control", J. of Aircraft, Vol. 39 (2), pp. 206-214, March-April 2002.

4. Mohan D Rao., "Recent Applications of Viscoelastic Damping for Noise Control in Automobiles and Commercial Airplanes", J. of Sound and Vibration, 262, pp.457-474.

5. Indranil D and Ron Hund., "Interior Noise Prediction of Hawker Horizon Aircraft Using Statistical Energy Analysis", NOISE-CON 2004, July 12-14, Baltimore, Maryland, pp. 333-346, 2004.

6. Michel van Tooren and Lars Krakers.,"Multi-disciplinary Design of Aircraft Fuselage Structures",

AIAA 2007-767, 45th AIAA Aerospace Sciences Meeting and Exhibit, 8-11 January, 2007, Reno, Nevada.

7. Cotoni, V., Gardner, B., Carneal, J and Fuller, C., "Modelling Methods for Vibro-acoustic Analysis of Commercial Aircrafts", 14th International Congress on Sound andVibration, Cairns, Australia, 9-12 July, 2007.

8. Kamal Idrisi., Marty E Johnson and James P Carneal., "Heterogeneous (HG) Blanket Design Strategies for Passive Control of Aircraft Interior Noise", Noise Control Engineering Journal, 56(6), Nov-Dec, 2008, pp.425-433.

9. Fuller, C. R., Elliott, S. J and Nelson, P.A., "Active Control of Vibration", Academic Press, 1997.

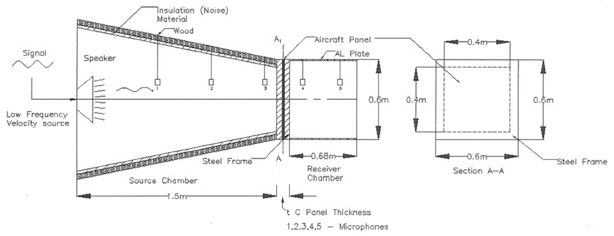
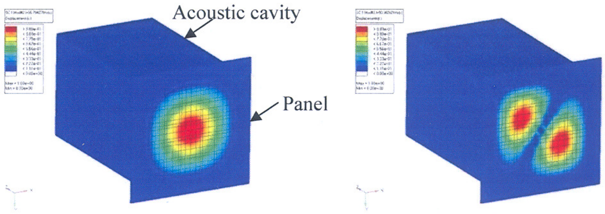
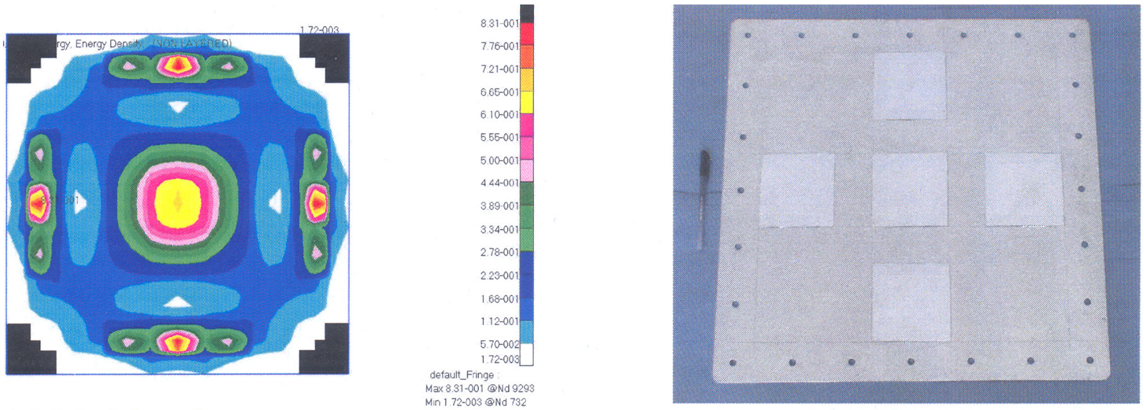


Fig. 1 Vibro-acoustic Test Facility (at STTD/NAL)



(a)Mode 1: 56.78 Hz (b) Mode 2: 93.96 Hz

Fig.2 Vibro-acoustic Mode Shapes



(a) Modal strain energy

(b) CLD patches

Fig.3 Optimal Locations for CLD Patches

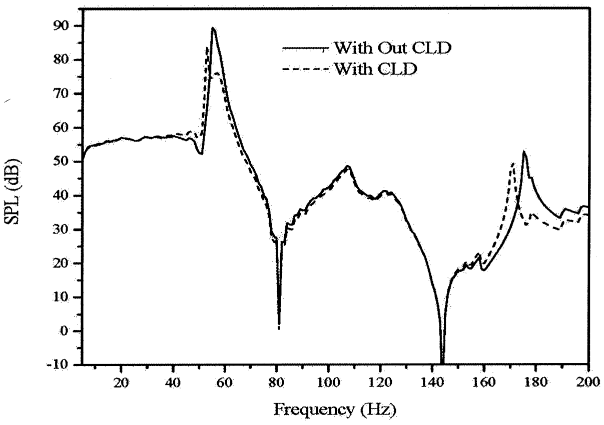
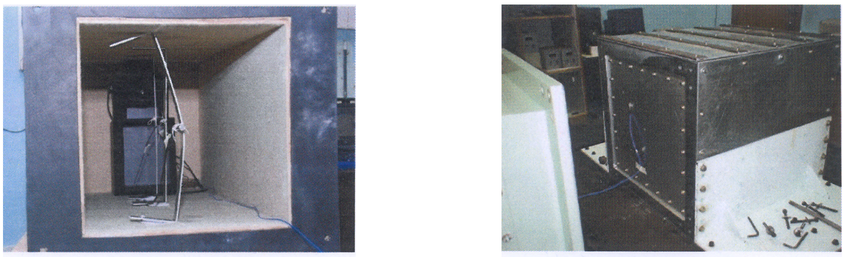


Fig.4 Vibro-acoustic Response Through Numerical Simulation



(a) Duct with speaker, mic

(b) Aluminium panel

(c) Side view

Fig.5 Experimental Setup

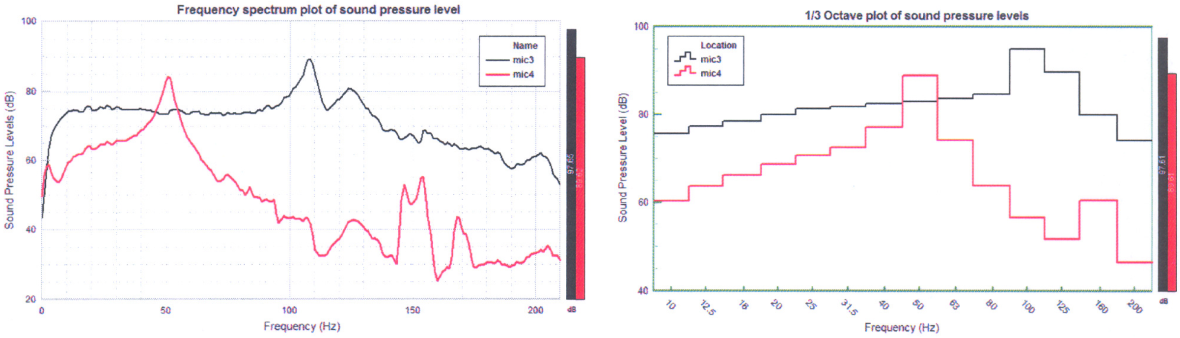


Fig.6 Aluminium Panel (without CLD)

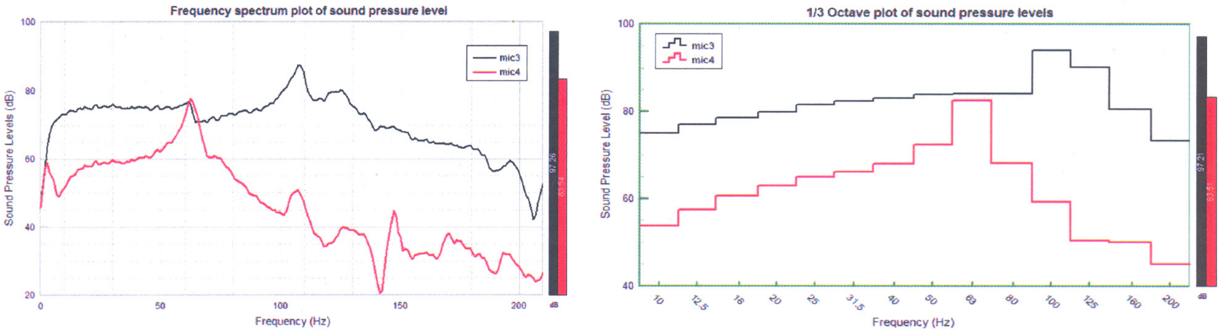
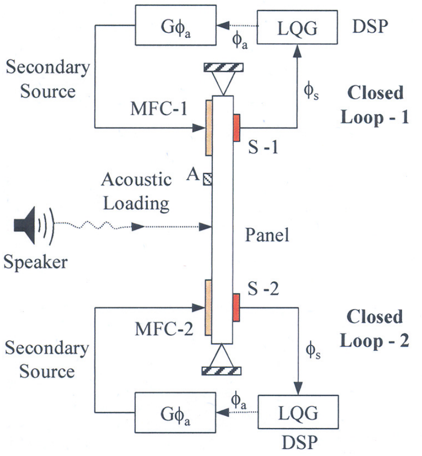


Fig.7 Aluminium Panel (with CLD) for Passive Control



S_1, S_2 : PZT Sensors
MFC : Macro Fibre Composite Actuators
G : Amplifier gain
ϕ_s : Sensor voltage
ϕ_a : Actuator voltage
A : Accelerometer (Observation)
LQG : Linear Quadratic Gaussian Control
(implemented in dSPACE DS1104)

Fig.8 Closed Loop Control Scheme (LQG)

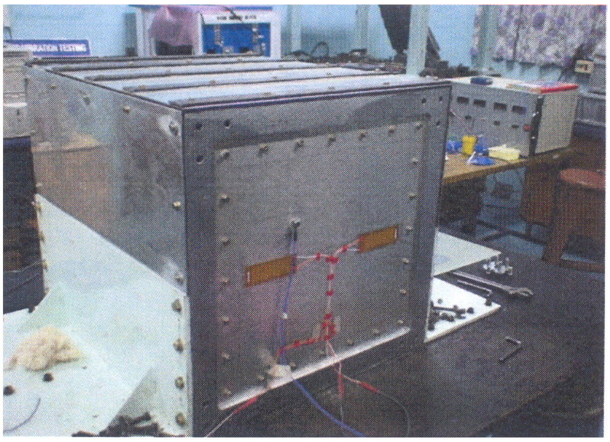


Fig.9 Aluminium Panel with Piezoelectric Composite Actuators (MFC)

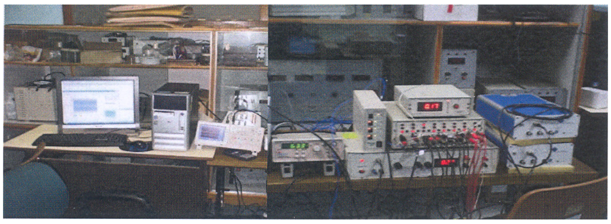
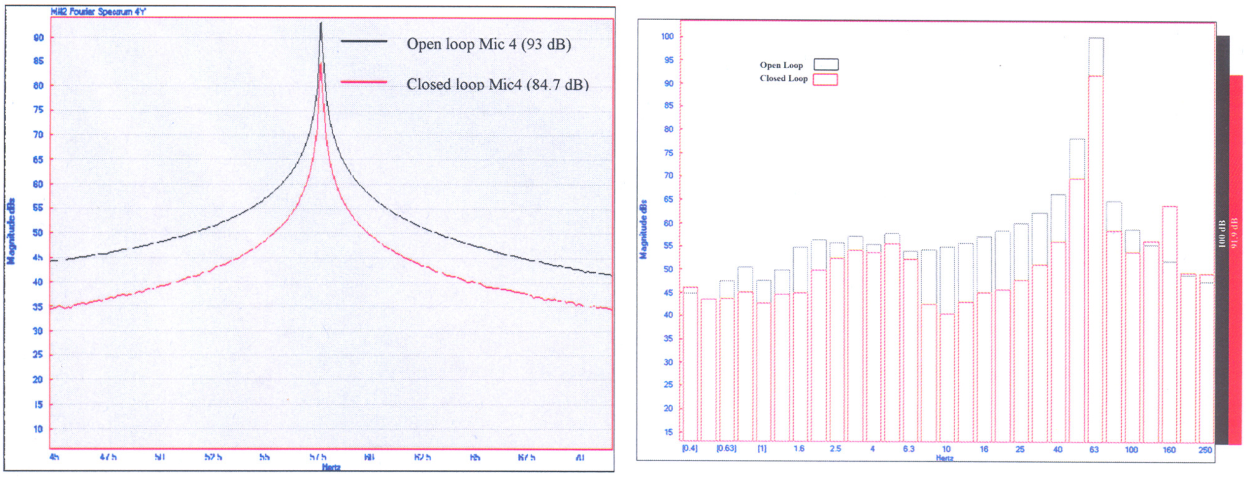


Fig.10 Control System Electrics for ASAC



(a) Fourier Spectrum *(b)* 1/3 Octave plot

Fig.11 Response of Mic4 with in-phase Actuation