FINAL TECHNICAL REPORT
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Project Title: **EFFECTIVE NOISE CONTROL FOR IMPROVED HEALTH AND SAFETY IN COAL MINES**

ICCI Project Number: 06-1/1.1D-4
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ABSTRACT

The principal objective of this project was to develop and evaluate effective strategies for reducing coal miners' exposure to audio noise to below a permissible level. The specific goals were to 1) design and evaluate a hybrid (active/passive) audio noise barrier (ANB) panel for transmission reduction of hazardous audio noise, 2) develop advanced strategies for on-line modeling and control of such hybrid ANB systems, and 3) investigate the development of virtual microphone concept for noise reduction inside closed cabins.

A hybrid ANB panel was developed consisting of aluminum sheet embedded with piezoelectric sensors and actuators for active noise control and polyurethane sheet for passive noise reduction. Advanced techniques were developed for robust on-line modeling and control of such protocol multiple-input multiple-output ANB systems. Experimental results showed significant reduction in noise-induced vibration of the hybrid ANB panel over a wide frequency range, with over 13dB reduction at specific frequencies. However, due to excessive computational requirements, verification of effective noise reduction in open spaces was not possible. The concept of virtual microphone control was also investigated for active noise reduction at selected targets in an enclosure. The experiments showed good results for fixed virtual targets.

Experimental results showed that advanced modeling and control strategies can indeed enable the development of effective noise control technology to reduce coal miners' noise exposure. Future research should consider integration of active noise control (ANC) using virtual microphones with ANB systems to develop effective mobile and economical strategies for miners' noise exposure reduction in coal mines.

EXECUTIVE SUMMARY

Objectives and Tasks

1) The overall objective of this research is to develop control strategies to effectively reduce coal miners' noise exposure to below a permissible level. The specific project objectives were to: 1) design a hybrid audio noise barrier (ANB) structure for noise transmission reduction, 2) develop modeling and control strategies for the ANB systems for real-time audio noise blocking, and 3) investigate the idea of virtual microphones control for active noise reduction in operator cabins.

Eight tasks were scheduled and performed to meet the project's objectives as follows:

- Task 1) Design analysis: Simulations and finite element analysis were carried out for the design of the ANB structure.
- Task 2) Platform set-up: Equipment and materials required for construction of a prototype multivariable ANB panel, with multiple sensors and actuators, as well as a test platform were acquired and assembled successfully.
- Task 3) Modeling and control: Advanced on-line modeling and control strategies were developed and successfully tested for the prototype multivariable ANB system for real-time noise reduction applications in coal mines.
- Task 4) Analog implementation: Design of low power analog circuits for real-time implementation of simplified control algorithms for the prototype ANB system was investigated and showed success in simple cases.
- Task 5) Virtual microphone strategy: The concept of virtual microphone (sensor) was investigated for active noise control. A strategy was developed for estimating audio noise at pre-specified locations with no microphone (virtual microphone location), using real microphones at other locations.
- Task 6) Virtual microphone control: Advanced on-line modeling, estimation and control strategies were developed and tested for real-time active noise reduction inside enclosures, using virtual microphone concept. The technique was shown to successfully reduce noise at a small zone around the virtual microphone.
- Task 7) Analog implementation of virtual microphones: Design of low power analog circuits for real-time implementation of simplified control algorithms for virtual microphone strategy was investigated. Virtual microphones with simplified analog controls could not produce acceptable noise reduction due to sensitivity of virtual microphone estimation.
- Task 8) Reports: All reports were prepared and submitted to ICCI regarding the progress of the project.

Introduction and Background

Audio noise at today's industries is perceived as the cause of most hearing losses in the United States, especially among coal miners. This perception is reflected in the recent standards set by Mine Safety and Health Administration (MSHA). The current standard states that all mines must use all feasible engineering and administrative controls to reduce miners' noise exposure to the "permissible exposure limit (PEL) of 90 dBA".

Noise control can be performed at the source, along the path, or at the receiver. Controlling the noise at the source aims to reduce the noise power through better mechanical designs. Noise control along the path tries to reduce sound energy by repelling or absorbing the sound as it travels in the environment, using devices such as barriers, walls, enclosures, and sound absorbing materials. Noise control at the receiver intends to reduce the acoustic pressure variation at the reception point, using devices such as ear-plugs and earmuffs. Noise control at the source site is typically more economical but may not always be feasible.

Noise control could be passive or active. In passive control the inherent acoustic characteristics of special materials are exploited to absorb or redirect the unwanted noise. These techniques are very economical, but unfortunately they are not satisfactory. In active control, an anti-noise is deliberately generated to counter the original noise. Active techniques have been shown to work well in laboratory settings but they have not been successfully implemented in real applications. This is due to their implementation complexity and their unacceptable cost. According to an MSHA report, most techniques that are currently successful in reducing miner's exposure to noise are passive techniques. However, these techniques so far do not satisfy the required noise level reduction.

It has been shown in the literature that passive techniques are effective in reducing audio noise in the high frequency range. Active techniques, on the other hand, are shown to be effective in reducing audio noise in low frequencies. The current research was to investigate a proper combination of active strategies with passive devices in developing an audio noise barrier (ANB) for noise absorption to effectively reduce miner's exposure to hazardous noise levels.

Experimental Procedures

Experiments were performed on a prototype audio noise barrier (ANB) structure in a test platform. Both the ANB and its test platform were constructed in-house, using digital signal processors (DSP) development system and materials purchased for the project. For the virtual microphone experiment, an available test platform was integrated with a DSP development system that was purchased for this project. The DSP development systems were equipped with Matlab/ Simulink software support for visual programming.

Testing the performance of the ANB system for noise absorption consisted of evaluating the effectiveness of various control strategies in reducing its noise-induced vibration. Experimental procedure for each test consisted of: 1) modeling the dynamics of the noise transmission channel through the ANB structure, and 2) designing a control strategy for reducing its structural vibration. For each test, a model of the noise transmission channel through the ANB structure was found numerically, using real measured data, for the purpose of control design. Then, appropriate control strategies to reduce the ANB's structural vibration were developed for the experimentally found model of the process and implemented digitally, using the DSP development system.

Testing the performance of a virtual microphone system consisted of measuring the audio noise reduction at the location of the virtual microphone, using a dummy microphone at that location for the purpose of verification only. Experimental procedure for each test consisted of: 1) modeling the noise transmission channel between the real and dummy microphones, as well as between the loudspeaker and the two microphones, and 2) designing an appropriate control strategy to reduce noise level at the virtual microphone location using the measurements at real microphone location. For each test, modeling, estimation of virtual microphone response and control designs were performed using real measured data and was implemented, using the DSP development system.

Conclusions and Recommendations

Results of the tasks revealed that noise reduction is a challenging and expensive process. Both audio noise barrier (ANB) and virtual microphone system designs worked well as expected from theoretical findings. Significant reduction in noise-induced vibration of ANB structure was achieved in 20-700 Hz frequency range with maximum reduction of 13dB in specific frequencies. However, both designs were found to be sensitive to modeling accuracy and control precision. Simplification of control designs and their analog implementation did not show much promise in performance robustness and cost effectiveness. This is particularly true for cases with multiple sensors and actuators.

For the ANB system to be effective, a large number of powerful piezo-actuators must be properly integrated into the structure for vibration control. Hence, for real applications, the structural development and their corresponding multivariable control implementation may become costly. Nevertheless, more research is needed to investigate other composite and active material for developing ANB systems with flexible curtain-like smart structures.

For virtual microphone systems, it was also found that noise reduction at a location where a microphone cannot be placed is indeed possible. However, the size of the region in which the noise is reduced is actually small. This limits the application of virtual microphone techniques to small spaces. However, even with small zone of reduced noise, it is possible to develop active virtual microphone systems for personal use, inexpensively. More research is need in this area for the development of personal wearable virtual microphone systems for active noise reduction.

Our future research direction is to combine ANB system with virtual piezo-sensor and virtual microphone strategies for active noise reduction. Our future research will focus on personal wearable virtual microphone systems for noise reduction, and on active control of hybrid flexible materials for noise blocking and absorption. We believe that with the current technology the recommended approach could result in effective noise control strategies.

OBJECTIVES

The overall long term goal of the proposed project was to develop advanced noise control strategies to effectively reduce coal miners' noise exposure in coal mines to below a permissible level. The specific project objectives for the current period were:

2) Design and evaluation of hybrid (active/passive) audio noise barrier (ANB) panels for noise transmission reduction.
3) Development and evaluation of advanced on-line modeling and control strategies for the designed ANB systems for real-time noise reduction applications in coal mines.
4) Investigation and evaluation of virtual microphones for active control and reduction of audio noise in operator cabins.

Eight tasks were scheduled as essential parts of this investigation in order to meet the project's objectives. The tasks were:

Task 1) <u>Design analysis</u>: Investigate the feasibility of various designs for hybrid (active/passive) audio noise barrier (ANB) panels for noise transmission reduction (noise absorption) using numerical and analytical techniques.

Task 2) <u>Platform set-up</u>: Construct a prototype of the proposed hybrid audio noise barrier (ABN) panel, consisting of an aluminum sheet embedded with piezoelectric sensors and actuators and polyurethane sheets. Also, construct a test platform consisting of a Plexiglas enclosure with noise generating loudspeaker, data acquisition system and a microprocessor development board for algorithm development and testing.

Task 3) <u>Modeling and control</u>: Develop advanced on-line modeling and control strategies for the prototype multiple-input multiple-output (MIMO) ANB system for real-time noise reduction applications in coal mines.

Task 4) <u>Analog implementation</u>: Investigate the design and implementation of low power analog circuits for real-time implementation of the simplified control algorithms on the prototype ANB system.

Task 5) <u>Virtual microphone strategy</u>: Investigate robust estimation strategies for virtual microphones for active noise control at pre-specified remote targets in operator cabins.

Task 6) <u>Virtual microphone control</u>: Develop advanced on-line modeling, estimation, and control strategies for virtual microphone system for real-time noise reduction applications in noisy enclosures.

Task 7) <u>Analog implementation of virtual microphones</u>: Investigate the design and implementation of low power analog circuits for real-time implementation of simplified control algorithms on virtual microphone system.

Task 8) <u>Reports</u>: Prepare and submit brief monthly reports to ICCI regarding the progress of the project. Also, prepare and submit a detailed final report to ICCI explaining the achievements and findings of the project and the future directions of the research.

INTRODUCTION AND BACKGROUND

Noise-induced hearing loss is perceived as a serious occupational disease among coal miners. This perception is reflected in the recent guidelines set by Mine Safety and Health Administration (MSHA). The guideline requires all mines to use all feasible engineering and administrative controls to reduce miners' noise exposure to the "permissible exposure limit (PEL) of 90 dBA".

Noise control can be performed at the source, along the path, or at the receiver. Controlling the noise at the source aims to reduce the noise power through better mechanical designs. Noise control along the path tries to reduce sound energy by repelling or absorbing the sound as it travels in the environment, using devices such as barriers, walls, enclosures, and sound absorbing materials. Noise control at the receiver intends to reduce the acoustic pressure variation at the reception point, using devices such as ear-plugs and earmuffs. Noise control at the source site is typically more economical but may not always be feasible.

Noise control could be passive or active. In passive control the inherent acoustic characteristics of special materials are exploited to absorb or redirect the unwanted noise. These techniques are very economical, but unfortunately they are not satisfactory. In active control, an anti-noise is deliberately generated to counter the original noise. Active techniques have been shown to work well in laboratory settings but they have not been successfully implemented in real applications. This is due to their implementation complexity and their unacceptable cost. According to an MSHA report, most techniques that are currently successful in reducing miner's exposure to noise are passive techniques. However, these techniques so far do not satisfy the required noise level reduction.

This research considered a proper combination of active strategies with passive devices to effectively reduce miner's exposure to an acceptable noise levels. Specifically, the project objectives were: 1) to design and test a composite structure consisting of an actively controlled smart structure with embedded piezoelectric elements and passive sound barrier devices such as polyurethane foams or fiberglass sheets for noise control, 2) to investigate control strategies and real-time computational techniques to make such systems feasible for noise reduction applications in coal mines, and 3) to investigate the implementation of virtual microphones and modal filters for active control of noise in operator cabins. Such quiet cabins equipped with video devices for remote monitoring can reduce operators' exposure to noise. Numerical analysis, using Matlab, and hardware experimentation were to be carried out to verify the effectiveness of the designs.

EXPERIMENTAL PROCEDURES

The specific objectives of the project for the current period included: 1) Design and evaluation of hybrid (active/passive) audio noise barriers (ANB) for noise transmission reduction, 2) Development and evaluation of advanced on-line modeling and control strategies for the designed ANB systems for real-time noise reduction applications in coal mines, 3) Investigation and evaluation of virtual microphones for active control and reduction of audio noise in operator cabins.

Audio signals are generated by mechanical vibrations that are transmitted through air and cause acoustic pressure variations, i.e., variations in atmospheric pressure within the audible frequency range. Variations in acoustic pressure are then sensed by human ears as audio signals. Transmission of audio sound requires a medium (solid, liquid, or gas) that can vibrate. That is why sound cannot travel in vacuum. Audio signals can propagate through various intermediate mediums by the way of traveling vibration before they reach the ears through air. Increasing the magnitude of vibration causes an increase in the magnitude of the variation of the acoustic pressure in the air, which in turn results in perception of louder audio signal. Conversely, active reduction of the magnitude of vibration in an intermediate transmitting medium causes a reduction in the variation of acoustic pressure in the air at the receiving end and reduces the perceived loudness of the transmitted audio signal.

The principle idea in designing an audio noise barrier (ANB) system is to construct an intermediate transmitting medium with an active control mechanism to effectively reduce its vibration in the frequency range of interest. The proposed hybrid ANB system design is indeed based on this idea. The experiments focus on implementation and evaluation of various robust control designs for reducing vibration in the constructed hybrid ANB system, in a desired band of frequency.

All audio noise barrier (ANB) experiments were performed on a prototype ANB structure using a test platform. Both the ANB and its test platform were constructed in-house, using digital signal processor (DSP) development system and materials purchased for the project. The DSP development systems were equipped with Matlab/ Simulink software support for visual programming.

Testing the performance of the ANB system for noise absorption consisted of evaluating the effectiveness of various control strategies in reducing its noise-induced vibration. Experimental procedure for each test consisted of: 1) modeling the dynamics of the noise transmission channel through the ANB structure, and 2) designing a control strategy for reducing its structural vibration. For each test, a model of the noise transmission channel through the ANB structure was found numerically, using real measured data, for the purpose of control design. Then, appropriate control strategies to reduce the ANB's structural vibration were developed for the experimentally found model of the process and implemented digitally, using the DSP development system.

Also, a technique known as "virtual microphone" has recently been developed to reduce audio noise in a pre-specified location using a microphone at a different location [1]. The technique is valuable when it is not desirable, or physically feasible, to place a microphone at the target location where noise is to be reduced. A set of experiments were carried out to investigate the effectiveness of virtual microphone technique in reducing audio noise at a pre-specified target location (location of virtual microphone) using a microphone for audio noise measurement at a different location. For the virtual microphone experiment, an available test platform was integrated with a DSP development system that was purchased for this project.

Testing the performance of a virtual microphone system consisted of measuring the audio noise reduction at the location of the virtual microphone, using a dummy microphone at that location for the purpose of verification only. Experimental procedure for each test consisted of: 1) modeling the noise transmission channel between the real and dummy microphones, as well as between the loudspeaker and the two microphones, and 2) designing an appropriate control strategy to reduce noise level at the virtual microphone location using the measurements at real microphone location. For each test, modeling, estimation of virtual microphone response and control designs were performed using real measured data and was implemented, using the DSP development system.

RESULTS AND DISCUSSION

Eight tasks were scheduled as essential parts of this investigation in order to meet the project's objectives. Here, experimental results in each task are presented and their significance with respect to the objectives of the project is explained.

Task 1 – Design analysis:
In this task the objective was to investigate the feasibility of various designs for hybrid (active/passive) audio noise barrier (ANB) system for noise transmission reduction using numerical and analytical techniques.

For the purpose of analysis, design of a simple generic structure was considered as the building block for the construction of the composite sound barrier panel. From our preliminary investigations, it was decided that a square-shaped composite panel should be designed and analyzed for subsequent construction, testing and verification. The actual size of the square-shaped composite panel, however, was to be decided based on the results of the FEM analysis and various cost considerations.

Matlab/ Simulink were considered as our main software for numerical simulation. Commercially available software, COMSOL, which is based on Matlab was also considered for FEM simulation and analysis.

A number of FEM simulations for a square-shaped composite audio noise barrier (ANB) panel were carried out using COMSOL software. Attempts were made to set-up realistic conditions. Figure-1 shows the schematic of the simulated system, while Figure-2 shows a typical FEM simulation result.

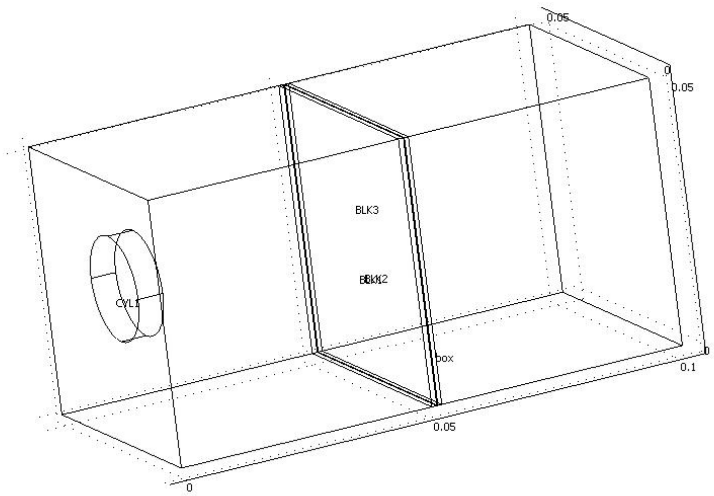


Figure 1 – Structural design of the ANB system

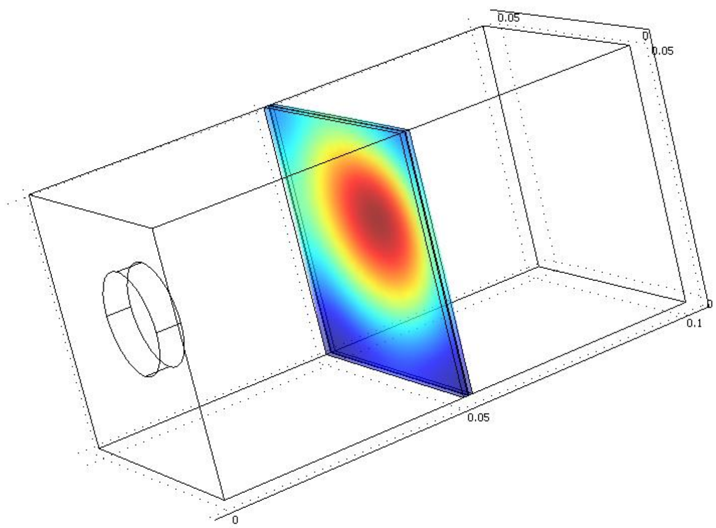


Figure 2 – FEM analysis of the ANB system

In general, the simulation results indicated that audio noise absorption by the composite panel is a function of the frequency band of the audio noise, as well as a function of the composition and geometric parameters of the panel. Based on the FEM analysis, a range of dimensions for the proposed square-shaped composite panel were chosen that were appropriate for subsequent experimental audio noise control.

<u>Task 2 – Platform set-up</u>:
In this task the objective was to construct a prototype of the proposed hybrid audio noise barrier (ABN) system, consisting of an aluminum sheet embedded with piezoelectric sensors and actuators, for active vibration control, and polyurethane foam sheets for passive noise absorption. In addition, a test platform was to be constructed consisting of

a Plexiglas enclosure with noise generating loudspeaker, data acquisition system and a DSP development system for algorithm development and testing.

Based on the numerical results, a prototype of the proposed hybrid audio noise barrier (ANB) structure was constructed. The ANB structure was a 2' x 2' board consisting of one sheet of aluminum and one sheet of polyurethane foam sandwiched together between two sheets of clear Plexiglas with a square shaped piece removed form the middle. The thickness of aluminum plate and the polyurethane foam sheets were respectively 0.5mm and 2mm, and the thickness of Plexiglas sheet was 1cm. In addition, using the same type of Plexiglas, a rectangular enclosure (box) was constructed as a test platform in order to carry out the experiments. The dimensions of the interior of the enclosure (box) were 2' x 2' so that the ANB structure could fit exactly in the middle of the box with a noise generating loudspeaker in one side, as shown in Figure 3. The ANB structure in the middle would then act as the noise barrier.

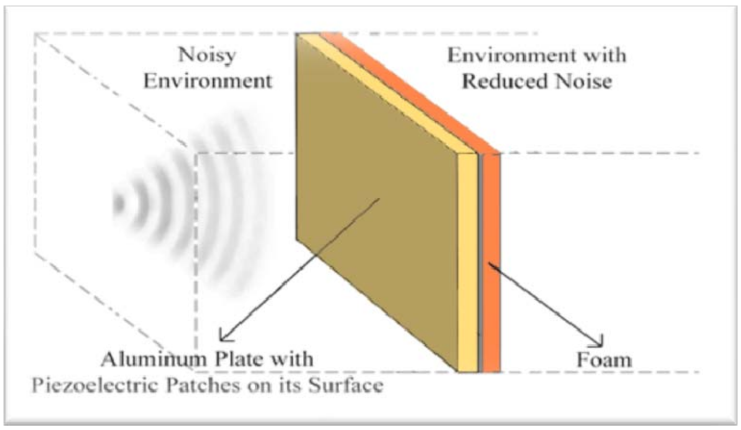


Figure 3 – Schematic of the ANB test platform

The aluminum sheet was embedded with piezoelectric ceramic patches, acting as sensors and actuators. The piezo-ceramic patches used were PSI-5H-S4-ENH of dimension L=72.4mm, W=72.4mm, and thickness=0.1905mm. The corresponding piezoelectric coefficients were: strain coefficient d_{31}=-320x10^{-12}, Young's modulus of elasticity Y_1^E=6.2x1010, and relative dielectric constant (@ 1Khz) K_3^T=3800. For actuators, the piezo-patches were cut into two, so the width of the piezo-actuators were W=36.2mm. For sensors, the piezo-patches were cut into four, so both the length and width of the piezo-sensors were L=W=36.2mm. The sensors and actuators were glued to the aluminum sheet on one side along its two diameters using silver-based (conductive) epoxy. The actuators were glued along the diameters at one-third intervals between the two corners. The sensors were glued toward the center along the diameter at one-third intervals between the two corresponding actuators along that diameter.

A rectangular box with a 2' x 2' interior cross-section was constructed from Plexiglas, with one side open. The ANB structure was placed in the middle of the box dividing it into two sections, one completely closed and the other open at one side. A noise generating loudspeaker was also placed inside the box at the closed subsection. The sensors and actuators were connected to a dSPACE ds1104 multiple-input multiple-output (MIMO) DSP development system through signal conditioning circuits and power amplifiers. A picture of the prototype ANB structure and the corresponding test-bed is shown in Figure 4.

(a)

(b)

(c)

(d)

Figure 4 – Experimental set-up: a) System components, b) ANB panel, c) Power amplifier, d) Digital processor front panel

Task 3 – Modeling and control:
In this task the objective was to develop advanced on-line modeling and control strategies for the prototype multiple-input multiple-output (MIMO) ANB system for real-time noise reduction applications in coal mines, using digital processors.

An effective control system design requires the knowledge of a low-order model of the system that is accurate over an adequate frequency range of operation. The most important requirement for a practical control design is the stability of the closed-loop system. In addition, the control design must be robust to inevitable modeling errors and external disturbances.

Based on vibration theory, the propagation of audio signals in a medium can be modeled as an infinite dimensional linear time-invariant (LTI) system [2]. However, over a band-limited frequency range, such model can be adequately approximated by a finite order LTI system for the purpose of control design. The steps for an effective control design is then to find an accurate low-order model of the audio noise propagation in the medium, experimentally, and then design a stable control strategy based on the acquired model of the system that is robust to modeling errors and external disturbances.

The process of modeling, control design and digital implementation becomes more difficult when the system consists of multiples of actuators (inputs) and sensors (outputs), i.e., the case of multiple-input multiple-output (MIMO) system. This is the case with modeling, control design and its digital implementation for the proposed audio noise barrier (ANB) system. All the designed algorithms were developed and implemented using dSPACE ds1104 DSP development kit with Matlab/Simulink support. The analytical developments, experiments, and verification for this task are explained in the following.

Modeling and identification:
A novel robust Kalman filtering strategy was developed for on-line experimental modeling and identification of MIMO, LTI systems in state space form that is applicable to the proposed ANB system [3]. The technique does not require the measurements of the system's states and generates a non-minimal model of the system, in state space form, using only the measurements of the system's input and output signals, without any differentiation [3-5]. The technique also generates an equivalent set of measurable state variables that can be used in control design. This is a very important and useful result which allows for both modeling and robust optimal control design for LTI systems, using only input and output measurements. However, for MIMO systems the non-minimal model of the system results in non-minimal order control dynamics which is computationally expensive for implementation.

To overcome the above problem, a novel robust model reduction technique was developed for non-minimal MIMO models of LTI systems, which is applicable to both stable and unstable systems [5]. The technique uses an H-infinity model reduction strategy, based on linear matrix inequality (LMI) and convex optimization methods. The technique guarantees that the modeling error for the resulting low-order MIMO model of the system has an H-infinity norm less than a pre-specified small number.

The experimental procedures for each test are explained as follows. First, the model of the ANB system with two-inputs and two-outputs was found experimentally, using both one-frequency-at-a-time (OFAAT) and the developed robust Kalman filtering (RKF) techniques. The frequency responses of the resulting models are shown in Figure 5.

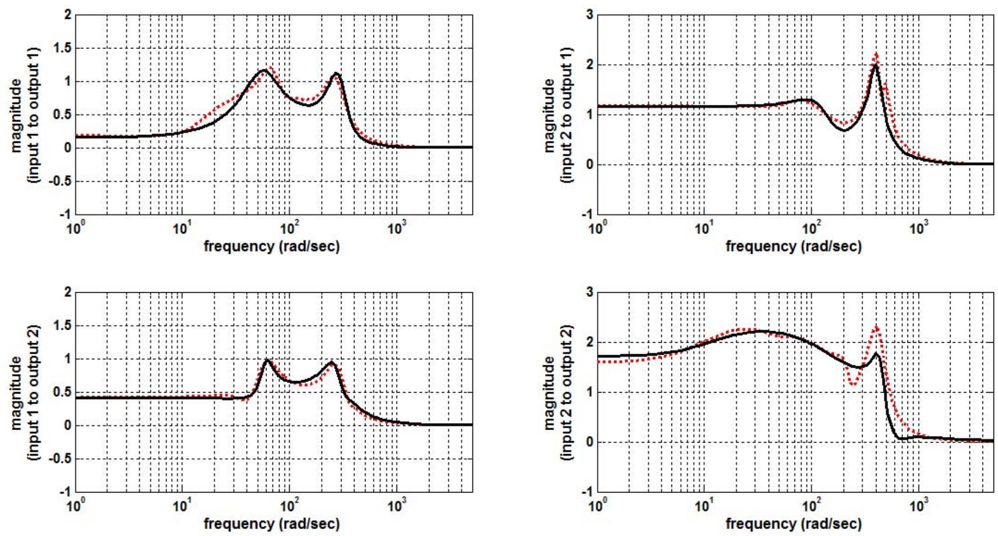


Figure 5 – ANB system model using OFAAT (dot) and RKF (solid)

From the RKF modeling results, the 2-input 2-output model of the ANB system was found to be of 8th-order. The corresponding non-minimal state space model of the system was then found to be of 32nd-order. To avoid designing a robust control of 32nd-order, a robust H-infinity model reduction technique developed in this project was applied. The corresponding Hankel singular values (HSV) for the original 8th-order, non-minimal 32nd-order, and the reduced 4th-order models of the ANB system are shown in Figure 6.

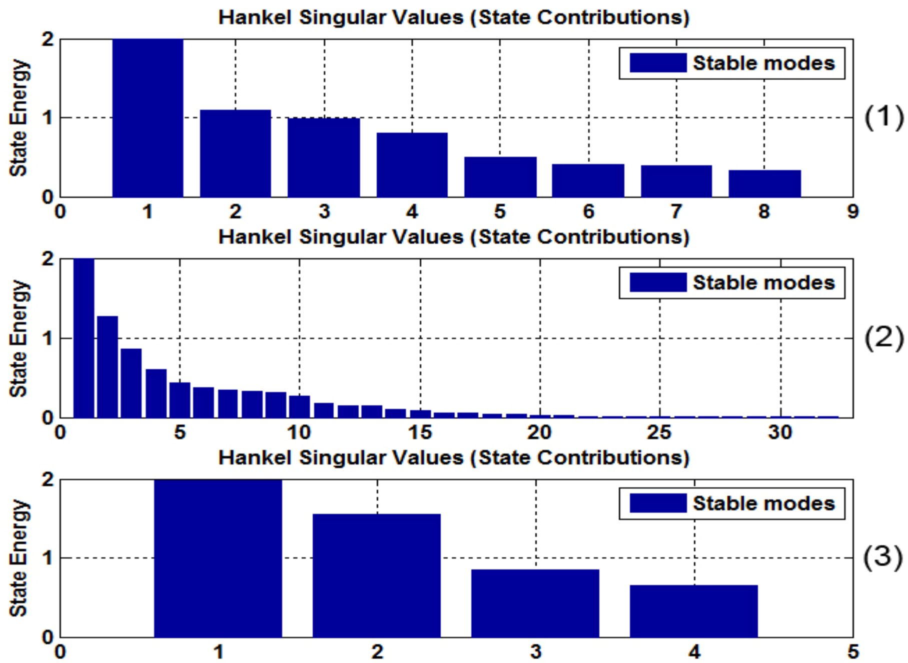


Figure 6 – HSV values for (1) original, (2) non-minimal, and (3) reduced-order models of ANB system

It is seen that the developed model reduction technique is able to generate a reduced-order model of the ANB system that accurately retains the primary Hankel singular values (HSV) of the original model. This is very important when the model is to be used for control design.

Control design:

Control designs for multiple-input multiple-output (MIMO) linear systems, based on individual input-output (I/O) channel control approach, in general, are not successful. This is due to the coupling between different I/O channels where any input designed independently to control a specific output could adversely affect the other outputs. Optimal control designs such as LQR and LQG, on the other hand, are based on optimization approach and are not influenced by the inter-channel I/O coupling effect. Their formulation is identical for both MIMO and SISO (single-input single output) systems. However, they require the exact knowledge of system's model and the precise measurement of system's states.

When optimal control approach is considered, the requirement for state measurement can be overcome using state estimation techniques. However, the condition on knowledge of the exact model of the system is generally not satisfied, which in turn results in performance degradation. To remedy this problem, robust optimal control strategies, such as H-infinity control, can be applied to MIMO systems with inexact models as long as bounds on the modeling errors are known. Robust controls can also handle systems with unknown state measurements. Consequently, using the robust modeling and model reduction techniques developed in this project, H-infinity control design strategies can be applied to the resulting reduced-order model of MIMO ANB system.

To realize an effective audio noise blocking system, a robust H-infinity control strategy with pole placement capability was developed for MIMO LTI systems. The H-infinity control technique with pole assignment capability developed here was then applied to the reduced-order model of the proposed ANB system for robust control and reduction of its noise-induced vibration.

The experimental procedures are explained as follows. Robust H-infinity control technique with pole placement was designed for both the original 8^{th}-order and the non-minimal 32^{nd}-order state-space models of the ANB system. The control algorithms were applied to the ANB system using ds1104 DSP development system. The Simulink block diagram of the controller is shown in Figure 7 and the results are shown in Figure 8.

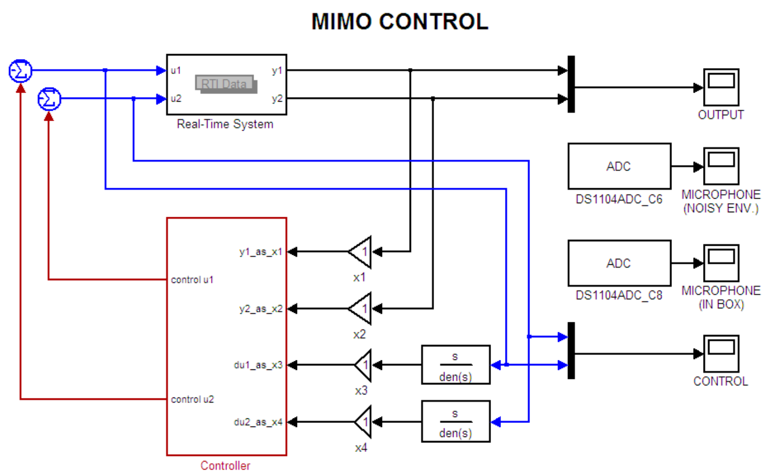


Figure 7 – Block diagram of the MIMO robust H-infinity controller

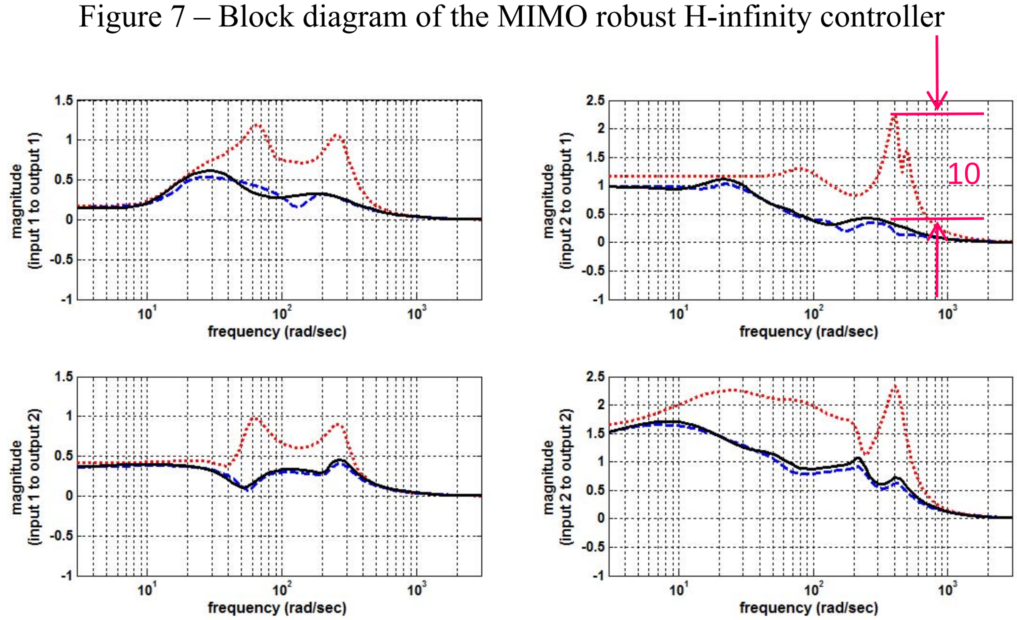


Figure 8 – Frequency response of ANB system with no control (dot), H-infinity control for original model (dash), and H-infinity control for non-minimal model (solid)

It is seen from the figure that both control strategies achieve significant vibration reduction in the ANB system in the frequency range of 20-700 Hz, with a maximum of 10dB reduction at 400Hz. However, the robust H-infinity control with pole placement designed for the non-minimal 32^{nd}-order model of the ANB system is able to reduce the noise-induced vibrations of the system slightly better than the control designed for the original 8^{th}-order model of the system.

To improve the results, various models of the system were found independently, using OFAAT technique, and were plotted in frequency domain in order to experimentally identify the lower and upper bounds for the modeling error. Finding the nominal model of the system, using RKF technique, and identifying the upper and lower bounds of the modeling errors in frequency domain, a new robust control strategy was developed based on linear matrix inequality (LMI) techniques that had superior performance in comparison to both LQG and H-infinity control methods. The LMI strategy is capable of quickly finding a feasible solution, numerically, as long as one such solution exists. The algorithm is based on convex optimization techniques and is carried out using Matlab's LMI toolbox.

The experimental procedures are explained as follows. First a nominal model of the ANB system was found using the developed RKF method. Then, using OFAAT technique, several models of the system were found experimentally and plotted in frequency domain together with the nominal model of the ANB system. The results are shown in Figure 9. It is seen that the frequency response plot of the nominal model of the ANB system is indeed in between those of its upper and lower models.

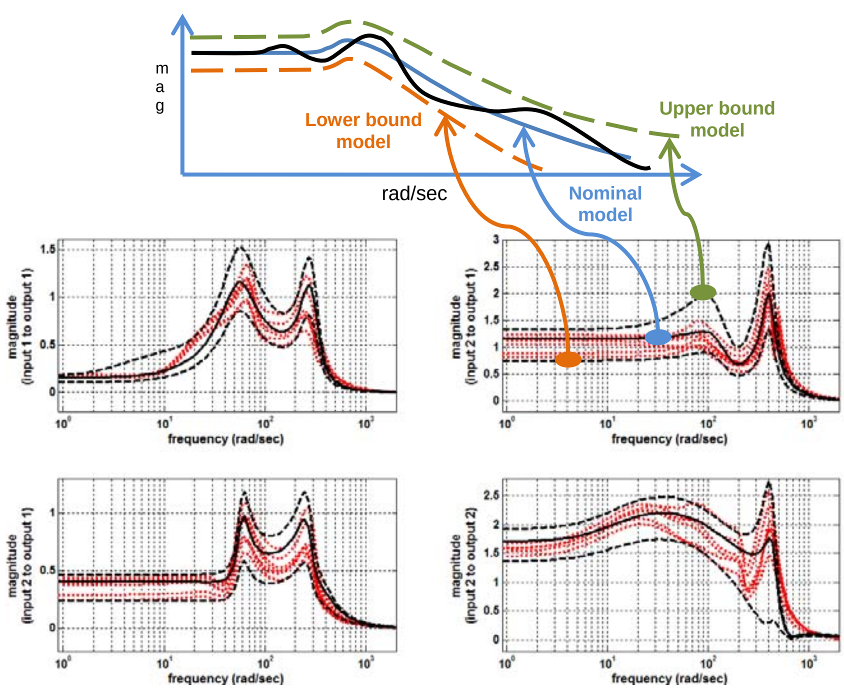


Figure 9 – ANB system models: various frequency models (dots), nominal model (solid), upper and lower-bound models (dash)

Next, the proposed LMI-based robust H-infinity control was designed for the nominal model of the system while simultaneously stabilizing the upper and lower-bound models of the ANB system. The resulting controller was successfully applied to the ANB system for reducing its noise-induced vibrations. The results are shown in Figure 10.

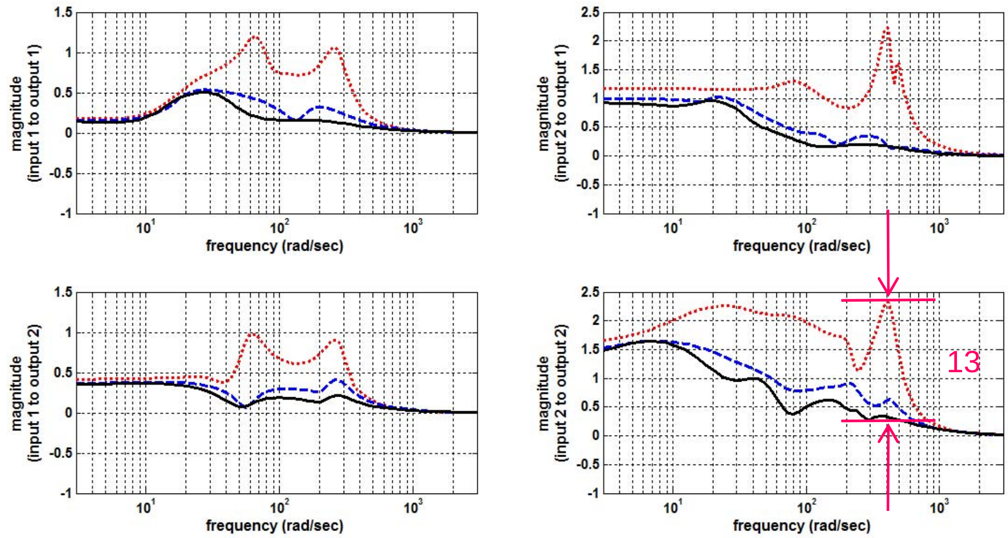


Figure 10 – Frequency response of ANB system with no control (dot), H-infinity control for nominal model (dash), and LMI-based H-infinity control for multiple models (solid)

It is seen again from the figure that both control strategies achieve significant vibration reduction in the ANB system in the frequency range of 20-700 Hz. However, the LMI-based robust H-infinity control with pole placement designed for the multiple models of the ANB system is able to reduce the noise-induced vibrations of the system much better than the control designed for only the nominal model of the system. The LMI-based control for multiple models was able to achieve a maximum of 13dB reduction in the noise-induced vibration of the ANB system.

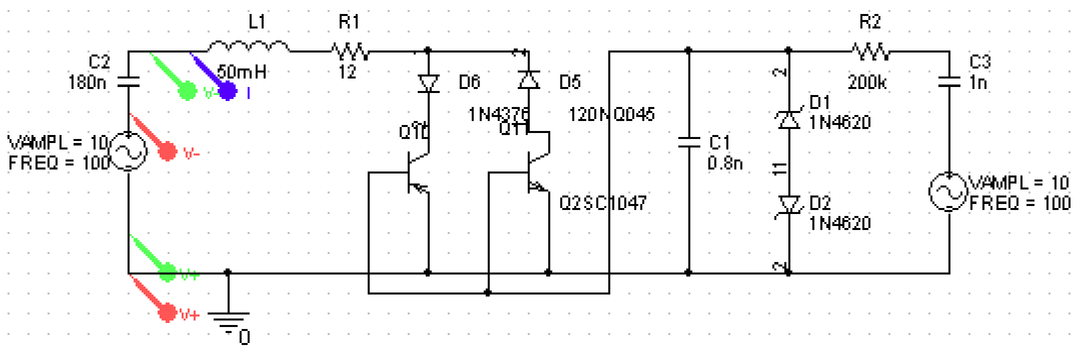
Several approaches were also used to simplify the developed robust optimal control strategies for easy real-time implementation. In most cases, the resulting time-invariant transfer function matrices corresponded to approximation of the original robust controllers in steady states. Using optimization techniques, slightly simplified controllers with approximate decentralization could be obtained without sacrificing performance.

Task 4 – Analog implementation:
In this task the objective was to investigate the design and implementation of low power analog circuits for real-time implementation of simplified control algorithms on the prototype ANB system.

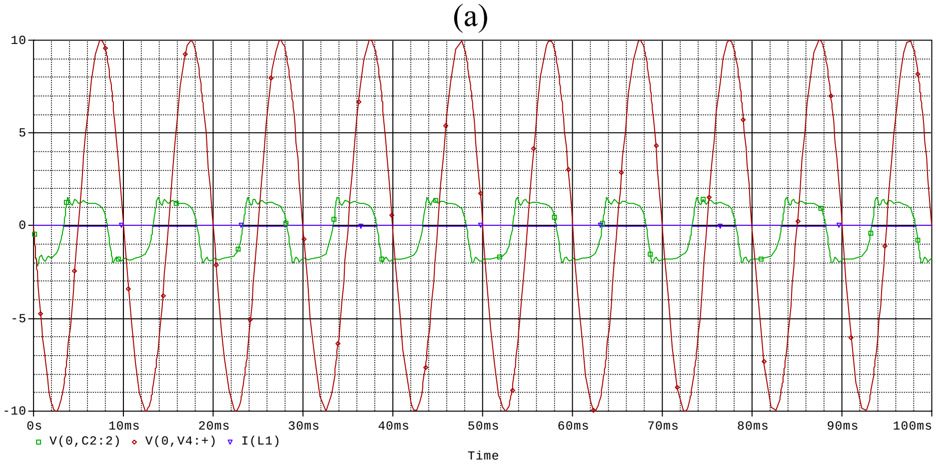
Effective implementation of a hybrid audio noise barrier (ANB) system, powerful enough to counter high energy noise-induced vibrations, requires high power embedded piezoelectric actuators. This in turn requires high-power high-voltage amplifiers for implementation of the control algorithms. Hence, it is economically advantageous if it is possible to implement such ANB systems using analog circuits for control processing and shunt circuits for low-power amplifiers.

Various analog electronic circuits were considered for economical implementation of the proposed hybrid ANB system. Among those, a shunt circuit design was considered that was capable of controlled switching of an R-L circuit in series with piezoelectric actuators for damping vibration [6, 7]. The required power for the switching operation and piezoelectric actuation was to be provided by the collocated piezoelectric sensors.

The corresponding tests were as follows. The corresponding shunt circuit was simulated to implement the on-off switching of an R-L circuit in series with a piezo-actuator, which was collocated with a piezo-sensor. The schematic of the shunt circuit and the simulation results, using PSpice, are shown in Figure 11.



(a)

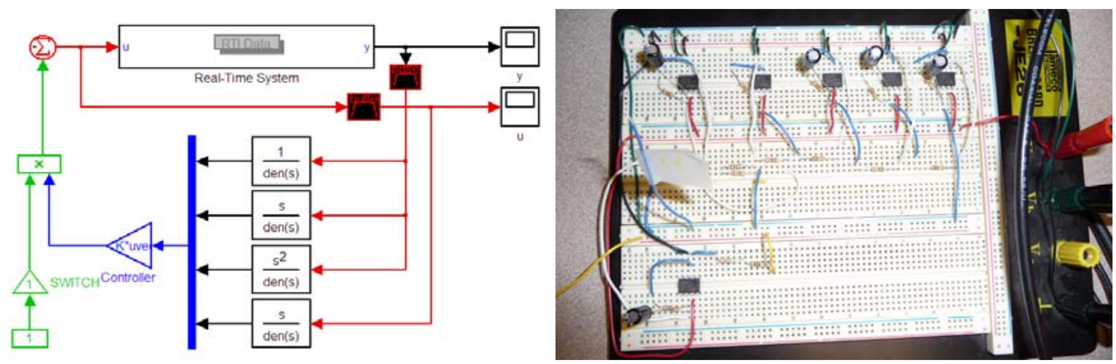


(b)

Figure 11 – Piezo-actuator response with shunt circuit, a) Circuit diagram, b) Piezo-actuator's internal voltage (Red), external voltage (Green), and current (Blue)

From the simulation results it was found that, in order to generate enough charge from the sensors to power the actuators, the approach requires piezoelectric sensors working in the direct 3-3 mode instead of the usual indirect 3-1 mode [7]. These composite fiber piezo-sensors are in the development stages and are not currently economical. It was then concluded that currently such design is not readily feasible.

To test the feasibility of analog controllers for real-time implementation of the ANB system, an op-amp based circuit was constructed to approximate a developed control strategy for single-input single-output case. In doing this, a robust H-infinity control was designed for vibration reduction of the ANB system in a SISO case, where all sensors were connected together and all actuators were connected together. The transfer function of the corresponding controller was then found and a circuit, using op-amps, resistors and capacitors, was constructed to approximate the designed controller's transfer function. The system response was found via digital implementation and attempts were made to also implement the control using the equivalent analog circuit. Simulink block diagram of the controller and the equivalent analog control circuit are shown in Figure 12 while the control result using digital implementation is shown in Figure 13.



(a) (b)

Figure 12 – SISO robust H-infinity control, a) Digital control block diagram, b) Analog control circuit

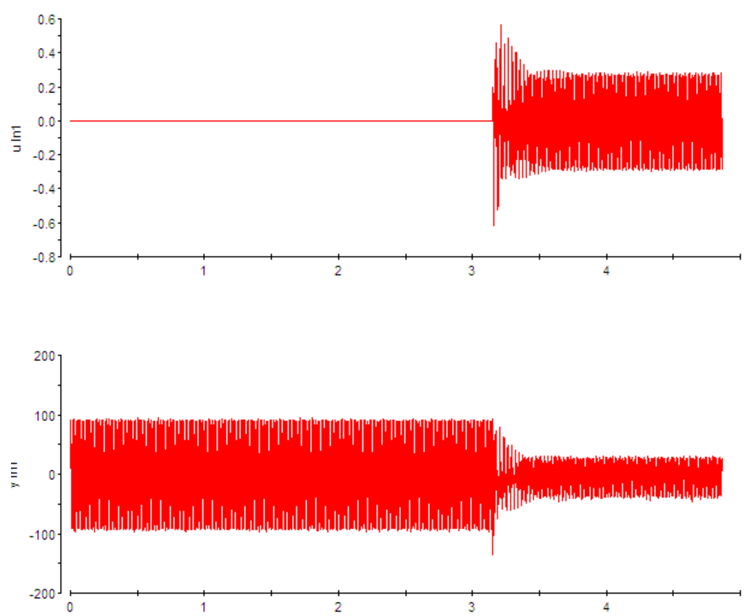
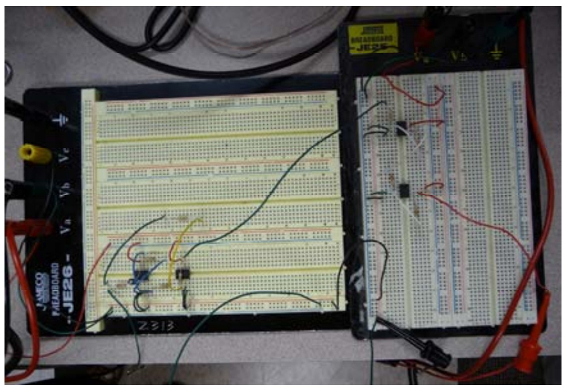


Figure 13 – ANB system response with digital control

As is seen from the figure, the digital implementation of the controller was able to reduce the noise-induced vibration of the ANB system. However, due to approximations and imprecision in the high-order analog circuit model of the controller, the circuit saturated and did not work.

Next, the designed controller was simplified further and a circuit equivalent of a PD control was constructed and successfully implemented. The simplified analog control circuit and the performance of the ANB system using simplified analog control is shown in Figure 14.



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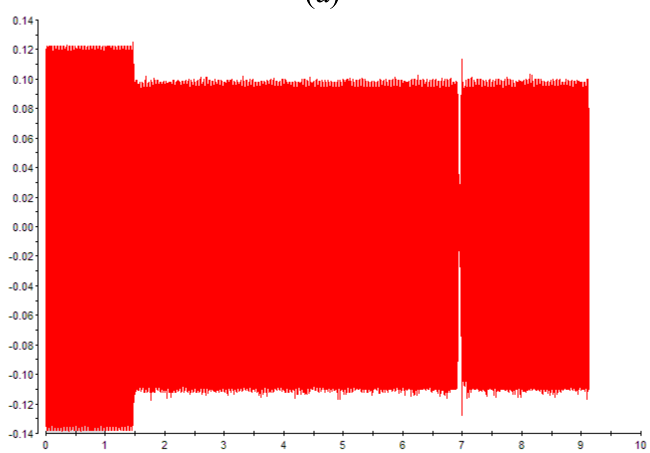


(b)

Figure 14 – Simplified ANB control, a) Analog circuit control, 2) ANB system response with simplified analog control

From the figure, it is seen that the simplified analog control was able to slightly reduce the noise-induce vibration of the ANB system. However, the performance of the digital controller was much better than that of the analog control. It was also realized that precise implementation of a designed control in multiple-input multiple-output (MIMO) case would be difficult, imprecise and uneconomical.

<u>Task 5 – Virtual microphone strategy</u>:

The objective of this task was to investigate robust estimation strategies for virtual microphones for active noise control at pre-specified remote targets in operator cabins.

Various techniques, including robust Kalman filtering, were considered with some success for estimation of noise levels at arbitrary locations inside a test platform, with no sensors at the target location. The estimation strategies were required to only use measurements from microphones planted at other fixed locations.

To improve the results a strategy similar to remote microphone technique [8] was developed for virtual microphone estimation. The technique is based on robust modeling of the transmission channel between the actual microphone and the virtual microphone by temporarily placing a real microphone at the virtual location, only for the purpose of modeling. The virtual microphone can then be accurately estimated as the output of the modeled channel by considering the real microphone measurement as the input to it. A schematic of the arrangement is shown in Figure 15. The performance of this virtual microphone estimation strategy can be further improved using robust Kalman filtering techniques.

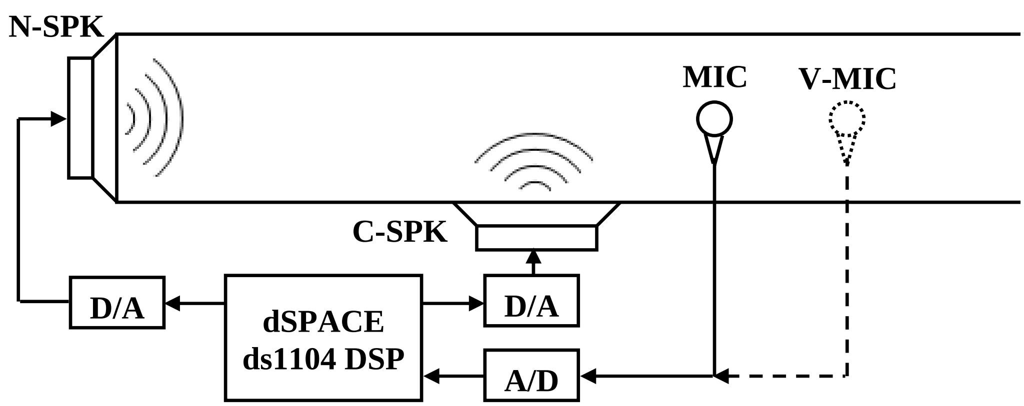
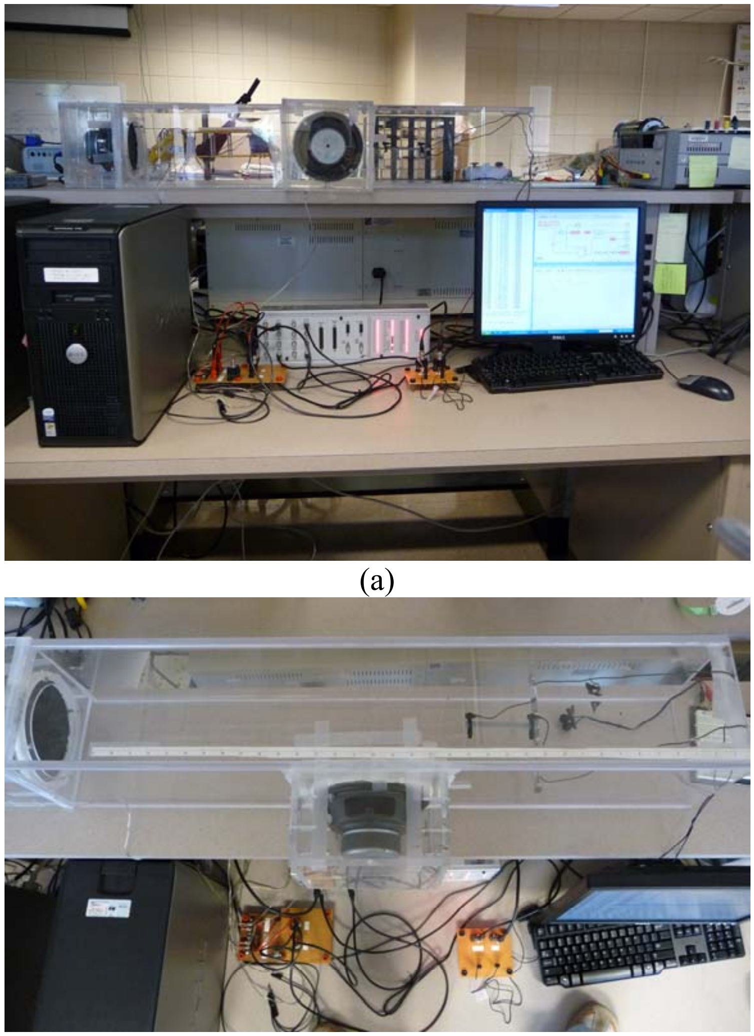


Figure 15 – Schematic of the virtual microphone arrangement

To test this concept, an available active noise control apparatus was considered for experimentation. The test apparatus consisted of a rectangular noise transmission channel (duct) made of Plexiglas with two loudspeakers embedded in the middle and one end of the channel. The loudspeakers at the end and the middle of the apparatus were considered, respectively, as the noise source and the control actuator. Two microphones were placed half way between the control speaker and the open end of the apparatus. The microphone closer to the control speaker was considered as the actual sensor/microphone and the one closer to the open end of the apparatus was considered as virtual microphone.

A ds1104 development system with Matlab/Simulink support was used for development and implementation of the algorithms. The experimental set-up is shown in Figure 16. The figure shows the complete test-bed including the duct with embedded microphones and loudspeakers, the ds1104 DSP front panel, and the interface electronics. The figure also shows a close-up picture of the noise conducting duct, for active noise control, with two loudspeakers and two microphones.



(a)

(b)

Figure 16 – Experimental set-up for virtual microphone strategy: a) System components, b) Active noise control apparatus

<u>Task 6 – Virtual microphone control</u>:
The objective of this task was to develop advanced on-line modeling, estimation, and control strategies for virtual microphones system for real-time noise reduction applications in noisy enclosures.

An effective estimation and control strategy for virtual microphone technique requires accurate low-order model of the transmission channel as well as stable, robust and effective real-time estimation and control techniques.

To test the developed algorithm, two accurate models were required. One was the model of the transmission channel between the actual microphone and a dummy microphone in the virtual microphone location. The other was the model of the transmission channel between the control speaker and the actual microphone. First the one frequency at a time (OFAAT) technique was used to identify the two transfer models necessary for virtual microphone control design. Then, H-infinity model reduction technique was used to determine accurate reduced-order approximates of these models. Then, a robust H-infinity control was designed for the transmission model from the control speaker to virtual microphone, which was found using series augmentation of the two previously found transfer models. The control is then implemented and the dummy microphone at the virtual location is used only to verify the performance of the designed control. Simulink block diagram of the virtual microphone controller is shown in Figure 17. The control results for both real microphone and virtual microphone arrangements are shown in Figure 18.

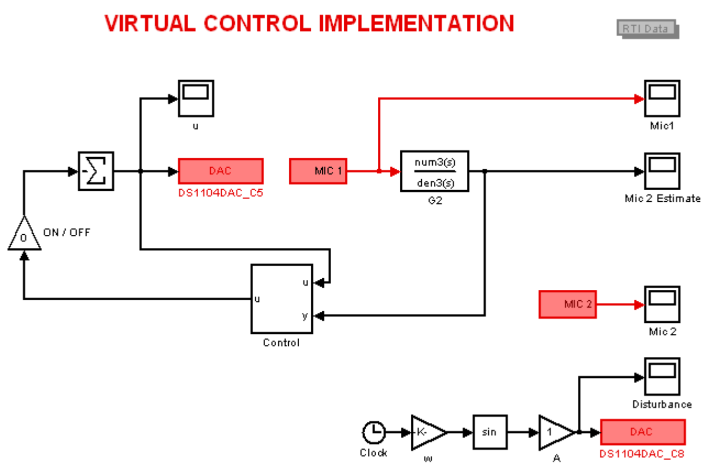
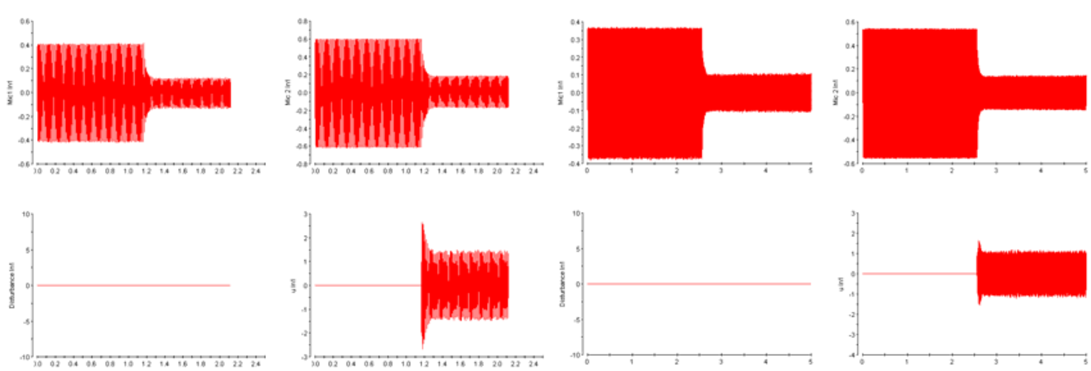


Figure 17 – Simulink block diagram of the implemented virtual microphone control



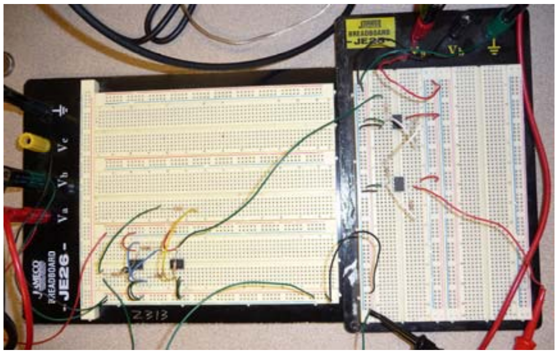
(a) (b)

Figure 18 – Active noise control with, a) Real microphone, b) Virtual microphone

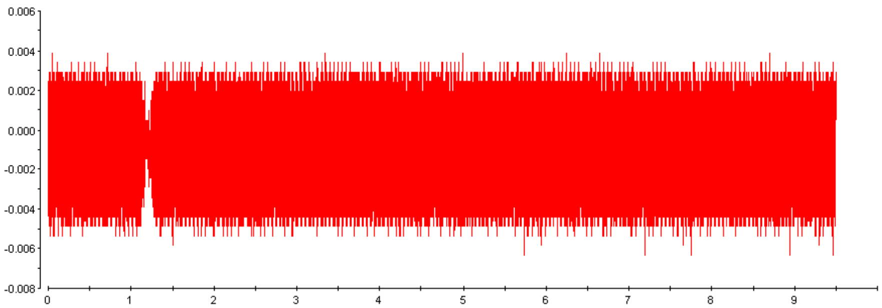
It is seen from the figures that the virtual microphone control strategy is indeed capable of noise control at a virtual location using an actual microphone placed at a different location. However, it was observed that the effectiveness of the virtual microphone control technique can be degraded noticeably when the geometry of the transmission channel changes. Additional research is needed to better understand and overcome this problem.

Task 7 – Analog implementation of virtual microphones:
The objective of this task was to investigate the design and implementation of low power analog circuits for real-time implementation of simplified control algorithms on virtual microphone systems.

Design of low power analog circuits for real-time implementation of simplified control algorithms for virtual microphone systems was investigated. Op-amp circuits were considered for realization of simplified controllers and were applied for noise reduction in virtual microphone arrangement. Virtual microphones with simplified analog controls could not produce acceptable noise reduction due to sensitivity of virtual microphone estimation algorithm. The simplified analog control circuit and the performance of the virtual microphone system using simplified analog control are shown in Figure 19.



(a)



(b)

Figure 19 - Simplified virtual microphone control performance, a) Analog circuit control, 2) Virtual microphone system response with simplified analog control

As seen from the figure, due to sensitivity of the technique for estimating the response of virtual microphone, the analog control circuit made no significant reduction in the noise level at the location of virtual microphone. It was decided that analog implementation may not be a viable approach for virtual microphone systems.

Task 8 – Reports:
The objective of this task was to prepare and submit brief monthly reports to ICCI regarding the progress of the project, as well as to prepare and submit a detailed final report to ICCI explaining the achievements and findings of the project and the future directions of the research.

As per the Principal Investigator Guidelines, all monthly reports were prepared and submitted to ICCI regarding the progress of the project. Accordingly, this final report is being submitted to ICCI to explain the achievements and findings of the project and its future direction.

CONCLUSIONS AND RECOMMENDATIONS

Results of the tasks revealed that noise reduction is a challenging and expensive design process. Both audio noise barrier (ANB) and virtual microphone system designs proved to be working well according to theoretical findings. Significant reduction in noise-induced vibration of ANB structure was achieved in 20-700 Hz frequency range with maximum reduction of 13dB in specific frequencies. However, both designs were found to be sensitive to modeling accuracy and control precision. Simplification of control designs and their analog implementation did not show much promise in performance robustness and cost effectiveness. This is particularly true for cases with numerous sensors and actuators.

For the ANB system to be effective, a large number of high power piezo-actuators must be properly integrated into the structure for vibration control. Hence, for real applications, the structural development and their corresponding multivariable control implementation may become costly. Nevertheless, more research is needed to investigate other composite and active material for developing ANB systems with flexible curtain-like smart structures.

For virtual microphone systems, it was also found that noise reduction at a location where a microphone cannot be placed is indeed possible. However, the size of the region in which the noise is reduced is actually small. This limits the application of virtual microphone techniques to small spaces. However, even with small zone of reduced noise, it is possible to develop active virtual microphone systems for personal use, inexpensively. More research is need in this area for the development of personal wearable virtual microphone systems for active noise reduction.

Our future research direction is to combine ANB system with virtual piezo-sensor and virtual microphone strategies for active noise reduction. Our future research will focus on personal wearable virtual microphone systems for noise reduction, and on active control of hybrid flexible materials for noise blocking and absorption. We believe that with the current technology the recommended approach could result in effective noise control strategies.

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