Chapter 1

Introduction to Active/Passive Structural Acoustic Control

1.1 ***Motivation of Study***

Everyday the human ear receives and quantifies the various acoustic events that occur in our lives such as the sound of palm trees flapping in an ocean breeze, conversations in the next office, the buzz of an alarm clock or the clamor of rush hour traffic. The common thread of these events are that they are considered structure-borne sounds because they are either produced or conducted by vibrating solid bodies. However, the way we perceive or classify these various sounds are very different and range from pleasurable to virtually intolerable. The search to avoid or reduce noise that initiates symptoms encompassing physical discomfort and hearing loss is the responsibility of the noise control engineer. Most methods of noise control related to structure borne sound can be broadly classified into two groups: *passive control* or *active control*.

Passive sound control methods dissipate propagating acoustic waves through various damping mechanisms that do not require an external supply of control energy. Some examples are mufflers, barriers and sound absorbent materials. The use of distributed sound absorbent layers plays an important role in this research and is one of the most common, inexpensive, and reliable methods of reducing noise related to building structures and vehicles. A way to passively expand the frequency range of sound absorbent liners for aircraft power plants has been studied by Sobolev et al [1]. The geometric properties of these sound absorbent liners are chosen so as to reduce as much as possible the noise level at the rotational frequency of the fan impeller which determines the noisiness of the aircraft above the ground. Such liners operate at high sound levels and in high velocity air streams. In these conditions nonlinear effects become significant factors. As the component associated with the fundamental frequency is suppressed, its' harmonics come to the forefront. Consequently, the sound absorption range of the liner must be increased to a higher frequency range. In their study, Sobelev et al examined the acoustic properties of composite resonant sound absorbent liners. The broadband response is achieved by a sound absorbent liner constructed of blocks arranged in a repetitive pattern in two mutually perpendicular directions and incorporating several resonators (rectangular cavity with an opening in the face turned toward the incident sound) tuned to different frequencies. The resonator geometric parameters are used to determine the optimal liner impedance which yields maximum sound absorption at various harmonics in a desired frequency range. Comparison showed good agreement between experimental and calculated impedance characteristics of absorbent liners.

The use of passive foam layers is another common method of noise control. In noise control applications which employ passive foam layers, the air molecules in the interstices of the porous material oscillate with the frequency of the exciting sound wave. This oscillation results in frictional losses. Changes in flow direction and expansions and contractions of the flow throughout irregular pores result in a loss of momentum in the direction of wave propagation. These two phenomenon account for most of the energy losses in the high frequency range [2]. Modification of the surface mounting conditions of an acoustic foam layer has been investigated by Kang et al. [3] for increasing normal incidence sound absorption. They showed that that the acoustical performance of finite-depth foam layers is sensitive to backing boundary conditions and dependent on the orientation of the layer cut with respect to the foam's rise direction.

It is interesting to note that some materials, such as Fiberglass PF-105 blankets are so effective at high frequencies that a sound wave at 1000 cps is attenuated by 60 dB in traveling 1 ft! At low frequencies the story is much different. For example at 250 cps, the attenuation for Fiberglass PF-105 wall would only be about 10 dB [4]. Generally, it is impractical to use absorbent materials for low-frequency sound control due to the necessary added mass and bulk which would be of particular concern in applications where there are weight and/or space constraints.

Active sound control is a relatively new field and it's practical implementation has been directly related to the development of fast digital signal processors. Control is achieved by using a combination of acoustic or vibratory actuators and error sensors to perform destructive interference with the sound field generated by the source. The fundamental active control process requires that the signal from one or more error sensors is minimized by one or more control actuators. The typical approach to controlling unwanted noise is to simply make the structure stop vibrating completely, which will obviously reduce the sound radiation to zero. This is the "brute force approach" and is traditionally accomplished by using mechanical shakers that apply a transverse load to the structure [5,6]. The magnitude of the force is therefore related to the mass of the shaker. If the shaker is very light, the structure very heavy, and the frequency very low, the result is a shaker that only shakes itself and not the structure. A novel and more efficient tactic is to employ intelligent material systems. Intelligent materials systems are material systems with intelligence and life features integrated in the microstructure of the material system to reduce mass and energy and produce adaptive functionality [7].

The birth of intelligent material systems occurred in 1880 when Jacques and Pierre Curie discovered that quartz crystals produce an electrical charge when deformed. They also found that the same crystals change in dimension or strain when subjected to an electric field. They called this phenomena "piezoelectricity"- derived from the Greek for pressure electricity. Over the following years, researchers continued to develop better and more stable materials. Lead zirconate titanate (PZT) was first introduced in 1954, and has become the most widely used piezoceramic. Later it was discovered that organic polymers offered good piezoelectricity and that the polarized homopolymer of vinylidene flouride (PVDF) developed far greater piezo activity than any other synthetic or natural polymer [8].

One of the most mature application areas of intelligent material systems is in active structural acoustic control. Intelligent material systems have for the first time allowed researchers to demonstrate control of low-frequency noise as a result of the introduction of induced strain actuation and sensing. Active structural acoustic control using intelligent materials has been successfully implemented to attenuate the sound generated by vibrating beams, plates and shells [9,10,11]. In active control, it is particularly important to minimize the mass and energy needs of the controller. Being that not all vibrational modes radiate sound, the obvious solution is to sense the structural modes that are radiating the noise and use the actuators that are distributed throughout the structure to control only the highly efficient radiating modes. Induced strain actuators use the in-plane structural impedance of the structure to react against. Hence, they possess the ability to exert forces on a structure at low frequencies while requiring little mass as compared to conventional shakers, often by orders of magnitude, to perform effective control. Structural sensing is most efficiently provided by piezoelectric films due to their high voltage output which is approximately ten times higher than that offered by a piezoceramic for the same force input. The advantages of active control are that the controller can be made adaptive or sensitive to changes in frequency or the spatial distribution of the noise source. Due to the signal processing that is required, active control techniques perform best in the low- frequency region. The disadvantages of active control methods are that they may require considerable electrical power, are susceptible to instability and can sometimes generate additional unwanted noise known as “control spillover”.

A new class of noise suppression devices is emerging due to the need for compact, integrated control systems that overcome the performance restrictions offered by purely passive or active control systems. *Active-passive* hybrids use both active and passive elements in either series or parallel. The passive component represents the host matrix for the active component and carries the primary sound attenuation responsibility. The active component enhances the performance of the system by overcoming the limitations of the passive component in the low-frequency region. The active-passive approach is used in this research to develop a ”smart foam”. The smart foam design integrates a distributed piezoelectric polymer actuator (*the active component*) between individual layers of sound-absorbing foam (*the passive component*). A primary reason for the suitability of these components in smart foam design and active noise control are their similar impedance characteristics to air. The smart foam device is unique in that it adaptively modifies the acoustic impedance of a vibrating surface, yielding a net decrease in the radiated sound power, without the use of secondary control inputs directly mounted on the surface. This observation is particularly important when attempting to suppress the acoustic radiation from massive structures. For this application, the vibration control inputs to the structure would have to be massive requiring a huge amount of mechanical power to suppress the motion of the structure. Conversely, an active surface coating (i.e. smart foam) can be distributed over large areas to minimize the total power radiation of the structure, thereby bringing the power consumption of the control system into more practical limits. Furthermore, due to its’ compact nature, smart foam is significantly different from common active noise control techniques that use secondary acoustic sources (loud-speakers) in arrays around the primary noise source [12,13]. Other important advantages of smart foam are that it provides broadband sound control, increased controller reliability and decreased control spillover. One can envision numerous applications for smart foam such as in interior aircraft noise control where weight is a critical issue.

1.2 Recent Literature on Active Surface Treatments

Ruppel and Shields [14] studied cancellation of air-borne acoustic plane waves obliquely incident upon a planar phased array of active surface elements. The incident plane wave was generated with and the reflected plane wave sensed by plane surface transducers designed by the researchers. The array consisted of a printed circuit board ruled with long, thin conducting strips. The array was controlled through the use of a specially designed circuit which allowed a given analog signal to be applied to each element, after an appropriated delay. The implementation required both digital and analog circuitry. The work describes extended surfaces which react to an incident wave in a prescribed manner. If this reaction is such that the surface radiates a control wave 180^o out of phase with and of the same magnitudes the reflected wave, the reflected wave is canceled. Since the phase of an obliquely incident sound wave varies over an extended surface, an array of independently driven transducers is required to control the wavenumber and frequency of surface vibration. The surface was shown to perform well for 30-50 Khz sound.

An active noise control surface treatment for structural radiation suppression was presented by Mason et al. [15]. Their technique is based on sensing and minimizing the local volume velocity of the vibrating structure. Noise reduction is achieved by distributing an array of control devices over the surface of the radiating structure.. Each device which is controlled independently of the other devices, consists of a motion sensor, an analog control circuit, and a loudspeaker. The loudspeaker is driven such that it reduces the volume velocity of the radiating structure within its close proximity. An experimental verification of the concept is presented using a uniformly vibrating circular plate and a single noise control device. Broadband (50-500 Hz) sound reductions of 10-20 dB were achieved over a wide spatial area.

Johnson [16] examined the use of a piezoelectric double amplifier active skin to provide broadband acoustic radiation control of vibrating plates. Each active skin consisted of a set of parallel PZT-Brass-PZT bimorph legs covered by a speaker paper diaphragm. By exciting the PZT bimorphs comprising the flexible “leg” elements of the active skin, an amplified diaphragm response is obtained. Analytical investigations were performed for an active skin employing both farfield microphones or accelerometers as error sensors. In experimental studies, the active skin was applied as both a partial and a complete covering of a vibrating panel, leading to the conclusion that the active skin elements must be evenly distributed over a radiating surface for maximum acoustic power attenuation. These researchers have presented promising results in the area of active surface treatments for sound reflection and radiation control. However, using an active/passive approach would increase controller reliability and could decrease the amount of control energy required in the high frequency region.

An active-passive piezocomposite actuator has been experimentally developed and tested for underwater sound reduction [17]. The design of the active coating prevents an incident sound wave from reflecting off the acoustic boundary of an object submerged in a heavy fluid. The acoustic energy associated with the incident disturbance is absorbed out of the medium through a piezocomposite device in the coating and dissipated by internal electrical means. This coating consists of a piezoelectric ceramic actuator and piezoelectric PVDF sensors embedded in an elastomer. The sensor arrangement detects and separates the acoustic field into a signal in terms of the incident acoustic pressure wave. The signal is manipulated through an electronic network to generate an appropriate driving voltage. The actuator was tested in a water-filled pulse tube and echo reduction levels were measured over an extended frequency band for tonal excitations. Good reduction was achieved and results clearly indicate how the active component of the device overcomes the limitations of a purely passive elastic coating. The results also indicate that by optimizing the embedded sensor location one can tune the piezocomposite coating to yield maximum echo reduction in a certain frequency band. Lafluer et al. [18] studied acoustically active surfaces using piezorubber (powdered ferroelectric ceramic dispersed in a rubber polymer) as the transducing material. The experiment was carried out in an oil-filled sound tube to eliminate the need to encase the transducers in electrical insulation. It is demonstrated that with the single layer, either reflection or transmission can be eliminated, while both reflection and transmission can virtually be eliminated with a double layer. While the authors highlight the flexibility of piezorubber (can be implemented as a non-planar transducer) as its' most meritorious passive qualities, oscilloscope traces are presented indicating the passive sound attenuation capabilities of the transducer.

Another example of an active surface coating is Actively-controlled Constrained Layer Damping (ACLD), which is an active-passive hybrid composed of a visco-elastic damping material sandwiched between two piezoelectric layers [19]. The three layer composite ACLD when bonded to a vibrating surface acts as a smart constraining layer damping treatment with built in sensing and actuation capabilities. The sensing is provided by the piezoelectric layer, which is directly bonded to the vibrating surface. The actuation is provided by the other piezoelectric layer driven by a control voltage. With appropriate strain control, the shear deformation of the visco-elastic damping layer can be increased, the energy dissipation mechanism can be enhanced and the structural vibration damping ratio is increased. Analytical results involving beam vibration control show the ACLD treatment is superior to conventional active control damping, particularly in the low-frequency range (first three vibration modes of the beam).

Beyene [20] has implemented an active/passive noise control surface that consists of a layer of acoustic foam backed by an active wall positioned in front of an air cavity. The foam is excited by normal incidence plane waves propagating the cavity and the goal is to determine the active wall velocity for maximum absorption over a broad frequency range. The experiment is conducted in a standard impedance tube using a digital control algorithm. A novel control strategy was successfully implemented which consisted of minimizing the reflected wave (extracted by a wave deconvolution circuit) in the airspace. This creates a match between the impedance in the air cavity and the impedance of a plane wave in air. Increased absorption was observed in the 0-2000 Hz frequency range by combining the active and passive control techniques. This is a compact noise control approach since the error information is measured inside the air cavity.

One of the first studies involving the feasibility of smart foam in acoustic noise control involved low-frequency reflection control and was initiated in 1991 by researchers at VPI [21,22]. Subsequent research involved employing smart foam for radiation control applications. In the reflection control application, smart foam is used to minimize the reflected plane wave intensity of low-frequency sound. The smart foam is placed at the end of an impedance tube, the primary noise source consists of a loudspeaker located at the opposite end of the tube. An analog wave deconvolution circuit based on the two microphone technique, as used by Elliot [23], provides a real-time domain estimate of the reflected sound wave which denotes the error to be minimized. The reflected sound wave intensity is monitored for tonal excitations up to 2000 Hz, and indicates the broadband sound attenuation offered by the active/passive control technique. Further research at VPI [23,24] successfully implemented smart foam for control of sound radiation. Their smart foam design consists of a layer of sound absorbing foam which encapsulates a continuous, cylindrically-curved layer of PVDF. The PVDF actuator is intentionally curved to couple the predominantly in-plain strain associated with the piezoelectric effect and the out-of-plane motion, which is required to accelerate fluid particles and hence radiate sound away from the surface of the smart foam. The appropriate control signal is determined by a SISO (single input/single output), digital, feedforward control algorithm and microphone error sensors are used. The radiation control application implemented smart foam to suppress the sound generated by a vibrating, baffled piston in an anechoic environment. The smart foam was located on the surface of the noise source. The radiation directivity was measured for the untreated piston, the passive control case (no control signal supplied to the PVDF actuator), and the active/passive control case (with control signal supplied to the PVDF actuator). Global sound reduction was achieved for broadband random noise between 250 Hz-1600 Hz, with improved low-frequency sound control due to the active input of the PVDF. Further studies [24] show the potential of using an array of smart foam to suppress sound radiating from a vibrating plate. The minimization of sound transmission was studied by Guigou [25] implementing a device consisting of a single smart foam actuator bonded to a lightweight, rigid panel with an accelerometer mounted on the surface of the panel. The panel acceleration is related to the combined volume velocity of the source and the smart foam. Using a digital, feedforward controller, the sound transmission generated by a vibrating piston is reduced by minimizing the acceleration on the surface of the panel.

Bolton et al. and Green [26,27]. presented analytical studies showing that at any angle of incidence, a finite-depth porous layer may be forced so as to create a perfect impedance match with an incident plane wave, thus causing the sound to be completely absorbed. Performance curves concerning the required force, displacement and control power using simplified actuator configurations denoted by embedded forcing planes were presented. Harmonic experimental results involving plane wave reflection control within an impedance tube were performed indicating the practical implementation of a smart foam. The proposed smart foam consisted of an active perforated piston backed by a passive foam block positioned at one end of the impedance tube. An excitation speaker driven by a harmonic signal generator was placed at the opposite end. An error signal proportional to the reflected sound field amplitude was produced using an analog deconvolution circuit. On average, the error signal was reduced by 40 dB. In addition to this work, a qualitative examination of various theoretical smart foam configurations was performed. The author's identified foamed PVDF as one of the strongest candidates for a successful smart foam arrangement.

1.3 <u>Organization of Thesis</u>

The introduction and development of smart foam for practical noise control applications is the primary goal of this research. Chapter 2 summarizes a preliminary noise control application using smart foam to suppress the sound generated by a vibrating, baffled, single degree of freedom piston in an anechoic environment. Harmonic and broadband sound control is studied using a SISO feedforward, Filtered-x LMS controller. During this initial experiment, the control mechanism provided by smart foam is identified. Special attention is given to maximize the radiation efficiency and minimize the nonlinear behavior of smart foam which is associated with its' physical curvature, mode shape and boundary conditions. Global sound reduction is measured and compared using either a near-field or far-field error microphone.

In Chapter 3, a more advanced problem is addressed involving plate radiation control using smart foam. The system has a distributed vibratory modal response and can be considered as a collection of independently-phased monopole sources. Accordingly, an array of smart foam modules are positioned on the plate surface in this experiment. Each module is autonomous and has an associated error microphone in its' local vicinity. A MIMO (multiple input/multiple output) feedforward, Filtered-x LMS controller is implemented for narrowband and broadband control sound control. For a more practical implementation, the reference signal used in the control algorithm is measured by an accelerometer on the plate. The amount of sound power reduction achieved is compared to the ideal case which uses a reference from the signal generator that provides the plate excitation.

Although these experiments show the merit of smart foam research in active noise control and identify procedures that can be used for improvement of the actuator, a more economical approach to smart foam design is to establish a computer code that simulates it’s performance. The establishment of a two-dimensional numerical model of smart foam in MATLAB$^{©}$ is outlined in Chapter 4. Following a historical overview of the theoretical modeling of porous materials, a Lagrangian formulation known as the Biot theory for sound propagation in elastic, porous media is presented. The identification of two compressional and one shear wave with their associated wavespeeds and attenuation coefficients is discussed. The energy expressions derived using Biot theory provide the foundation for the development of a numerical foam model using elastic-absorption finite elements. Since air is the operating medium associated with smart foam, an acoustic finite element model is derived. A method for coupling the elastic-absorption finite elements with conventional acoustic finite elements is discussed. A piezoelectric finite element model based on induced strain actuation is derived allowing the coupling between the absorption finite elements and the piezoelectric finite elements to yield a discretized model of smart foam. Various simulations of smart foam as an acoustic source are performed to establish the optimal smart foam configuration. The actuator mode shape and boundary conditions are varied and influence studied during the optimization.

Chapter 5 details a more practical noise control experiment in which smart foam is used as an active/passive liner to minimize sound propagation in an enclosure. The enclosure is a rigid-walled, long, rectangular duct, excited by an acoustic driver at one end and terminated by an anechoic wedge at the opposite end. The acoustic driver is positioned such that it excites the transverse acoustic modes allowing them to propagate down the duct toward the anechoic termination. A section of the wall of the duct is lined with a collective array of smart foam modules. Microphone error sensors are located downstream of the control actuators, along the transverse length of the duct, in order to provide the error information for a MIMO feedforward, Filtered x control algorithm. A full-scale numerical model of the duct acoustic control application is constructed and used to simulate the performance of smart foam. The purpose of the model is to study the sensitivity of this active/passive control approach relative to the spatial distribution of control channels and error sensors. A comparison of the numerical and experimental results is completed. These duct acoustic control studies are considered a fundamental step toward implementing smart foam in interior aircraft noise control applications.

Chapter 6 summarizes the important observations and accomplishments of this research and suggests topics for future work. The significance of this research is that it will provide a basis for the implementation of the active/passive smart foam technique to more complex/practical noise control problems.