

Chapter 6

Concluding Discussion

6.1 Key Accomplishments

The development of a “smart foam” which uniquely combines active and passive control methods for acoustic noise control applications was the primary focus of this research. Smart foam consists of a passive sound-absorbent foam layer with an embedded piezoelectric actuator, known as PVDF, which acts as an active acoustic control source. These components are chosen for smart foam because their impedance characteristics are similar to air. The composite actuator yields broadband noise reduction by simultaneously offering the high-frequency sound attenuation offered by an acoustic foam layer with low-frequency active sound control. The embedded piezoelectric component is physically curved to couple the in-plane strain with vertical displacement when excited by a voltage. The active control input is governed by a feedforward, Filtered-x LMS control algorithm such that the resulting vibration of the structural and acoustic phase of the foam generates a secondary acoustic field which destructively interacts with the primary noise source. One can envision a host of sound control applications for the lightweight, compact smart foam actuator ranging from vehicular noise control to noise reduction within

buildings. The key contribution of this research to the area of active noise control is the integration of the passive foam with a distributed, active component embedded in its matrix. Although other researchers have proposed “actuation of foam” to yield increased low-frequency sound control, the practical implementation accounted for simple actuation techniques involving an active piston connected in series with a passive foam layer. The novelty of the smart foam proposed in this research lead to a host of unique studies to identify ways to increase the acoustic control authority by altering the configuration of the piezoelectric layer. To identify the feasibility of smart foam in active noise control, various experimental and numerical studies are completed which address radiation and enclosure noise control applications.

Initial experimental studies implemented smart foam to suppress the sound generated by a vibrating, baffled piston in an anechoic environment. Due to the monopole-like radiation pattern of this simple source, successful attenuation of tonal and random noise was obtained using a SISO (single input/single output) feedforward, Filtered-x LMS controller. The control mechanism involved modification of the radiation impedance of this simple source by the distributed smart foam actuator in order to achieve a global attenuation of sound radiation. Good broadband control was obtained owing to the complimentary nature of the hybrid active/passive control technique i.e. the active control component provides low-frequency sound reduction while the sound absorbent layer yields significant high-frequency noise control. Improving the sound output of the actuator proved to be an integral part of this study. Altering the control voltage polarity of neighboring transducers within the smart foam and using a thin bonding layer between the piezoelectric actuator and the foam layers accounted for increased actuator sound output and decreased nonlinear behavior.

The feasibility of implementing smart foam in a more advanced radiation control application involving a system that has a distributed modal response was addressed. An array of smart foam modules were employed as an active/passive surface coating to minimize the radiated sound power of a baffled plate. Each module was autonomous and enclosed in a stiff frame to enhance the low-frequency sound output. Multiple error microphones were located in the nearfield of the smart foam array surface to minimize the sound pressure. Significant broadband acoustic power attenuation was achieved using a MIMO (multiple input/multiple output) feedforward, Filtered-x LMS controller and a reference from the signal generator that provides

the plate excitation. An alternate control scheme utilized the plate acceleration as a reference and yielded satisfactory results indicating the potential for more practical smart foam applications. Changes were made to the smart foam design which enhanced its acoustic strength in the low-frequency region.

The important conclusions from the previous experimental investigation of smart foam and piston radiation control are:

- *Global cancellation of harmonic and broadband noise induced by the simple source was successfully achieved by the smart foam. The potential of smart foam to globally reduce low and high-frequency sound while minimizing the nearfield or farfield sound pressure was also illustrated.*
- *The smart foam was configured with a single piezoelectric film formed into a series of half-cylinders of opposing physical polarity. Etching the boundary where the physical polarity of the actuator changes and alternating the applied voltage polarity of neighboring transducers promotes in-phase vertical movement of the active component. Consequently, a higher control sound output is gained*
- *Using a thin bonding layer between the piezoelectric actuator and the foam layers accounted for increased actuator sound output and decreased nonlinear behavior with respect to frequency.*

The important conclusions from the previous experimental investigation of smart foam and plate radiation control are:

- *It is shown that a collective smart foam array can be implemented as a noise control treatment to suppress the power radiated by a complex, radiating plate. The experimental setup offers a compact control arrangement by allowing the control actuators and error sensors to be located in a localized area near the primary source, while producing an overall reduction of the freefield radiated power.*
- *A further smart foam design improvement is accomplished by encasing each module in the smart foam array in a rigid frame. The purpose of the frame is to constrict the horizontal motion of the curved actuator which translates into increased vertical displacement. This accounted for an increase in the low-frequency control sound output of the smart foam.*

- *Implementing an internal reference signal, considerable active sound power reduction of random noise was achieved using a IIR LMS control code. Comparatively, a FIR control setup offered greater active sound attenuation over a wide frequency range. This indicated that a distributed smart foam array with independently-phased control inputs are necessary to minimize noise from a vibrating source with a distributed modal response. In each configuration, the sound attenuation was further increased due to the passive dissipation offered by the foam, particularly in the high-frequency range.*
- *Smart foam control performance was also studied using an external reference signal measured by an accelerometer on the plate which offers a more practical arrangement. Implementing an external reference signal provided slightly less attenuation in a narrower bandwidth compared to the control case that uses an internal reference due to coherence and causality issues.*

The previous experiments established the merit of smart foam research in structural acoustic noise control. A more economical approach to smart foam design is to establish a computer code that simulates its performance. The establishment of a two-dimensional numerical model of smart foam in MATLAB[®] allowed the investigation to improve the acoustic characteristics of the actuator by modifying several design parameters. Since air is the operating medium associated with smart foam, an acoustic finite element model is derived. A method for coupling the foam 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. The numerical code accounted for either a “triangular” or “cylindrical” physical orientation of the embedded piezoelectric actuator within the foam, and allowed fixed and free boundary conditions. In the 100 Hz f<math><1000</math> Hz frequency range. The major conclusion of the numerical investigation is:

- *It was shown that a series of cylindrically curved actuator with fixed ends yielded the highest sound output due to an increased surface displacement of the foam. With regard to the radius and wavelength of the curves, it was illustrated that the optimal PVDF configuration for low-frequency sound control accounts for the largest radius with a wavelength that does not power amplifier limitations or space constraints.*

An advanced noise control experiment in which smart foam is used as an active/passive liner to minimize sound propagation in a rigid walled duct was presented. This noise control problem is addressed as a fundamental step toward illustrating the potential of smart foam in interior aircraft and turbofan inlet noise control. The enclosure is represented by a rigid-walled, rectangular duct, excited by an acoustic driver at one end and terminated by an anechoic wedge at the opposite end to dissipate the longitudinal standing waves. A section of the wall of the duct was lined with a collective array of smart foam modules and established three control channels for minimizing the transverse propagating modes of the duct. Multiple transverse arrays of sixteen microphones are positioned upstream and downstream of the smart foam array. Most are observation microphones to monitor the sound pressure before and after control. A select number of microphones perform as error sensors located downstream of the control actuators and provide the error information for a MIMO feedforward, Filtered-x control algorithm. The major conclusions of this duct acoustic control study reveal:

- *Good active/passive attenuation of the transverse acoustic duct modes were achieved during both harmonic and broadband control in the $100 < f < 525$ Hz frequency range. This frequency range includes the first, second and third transverse acoustic modes of the duct.*
- *A modal analysis was performed to identify the acoustic modes and resonance frequencies of the duct by driving the excitation speaker with broadband noise and calculating the acoustic potential energy. A comparison of the energy for a rigid duct and a passively lined duct, both anechoically terminated, reveal that the passive foam liner damps the acoustic response within the duct and shifts the transverse modes to lower frequencies.*
- *The addition of the passive foam liner to the bottom duct wall alters the mode shape compared to the mode shape of the untreated duct. This is most prevalent in the higher frequency region and is attributed to the soft impedance of the foam liner compared to the rigid duct wall.*
- *The addition of the passive liner reduces the global sound levels within the duct. Passive sound attenuation increases as the ratio of the acoustic wavelength to passive liner length decreases. This indicates that an acoustic propagating wave will experience a significant loss of acoustic energy in the high-frequency range which is the intent of smart foam.*

- *The best control results are achieved when the dimension of the control system (i.e. the number of error sensors and control channels) is equal to the order of the mode to be controlled (i.e. there is one control channel and one error sensor per wavetype). The error sensors correspond to points of maximum reduction when they are located at points of maximum sound pressure levels for the passive control case.*
- *For good control results, the location of the smart foam control array and the error sensors should be away from the nearfield of any acoustic sources.*
- *Several numerical simulations related to this duct acoustic control experiment are presented and the results are compared to the experimental data. The comparison reveals similar trends indicating that the numerical smart foam model operating in an acoustic environment is a valuable control system design tool.*

6.2 Future Work

Further research concerning the implementation of smart foam in active noise control applications will require more numerical and experimental studies. The numerical model of the smart foam actuator presented in this thesis contained frequency-dependent mass and stiffness matrices which resulted in time consuming and laborious calculations when studying the response of the actuator as a function of frequency. This limitation must be overcome in order to develop large-scale numerical models of noise control problems with smart foam. Additional numerical studies are warranted to identify smart foam actuator configurations that exhibit increased low-frequency sound output. These numerical models may also investigate optimization of the passive foam properties which was not dealt with in this research. Further experimental investigations will deal with more complex problems which may involve controlling the acoustic modes of an irregularly shaped enclosure. This problem may require treating separate sections of opposing walls of the cavity with a smart foam liner. Studies concerning actuator/error sensor placement and acoustic coupling of actuator control sound fields would be an integral part of the investigation.