

Chapter 1

Beginning

“Love has no rhyme, no reason, nor no season.”

Robert Earl Keen Jr.

1.1 Introduction

A topic studied for many years is how to perfect sound reproduction. As far back as records of history will provide, sound in some form has filled voids in our lives, created moments of peace, held us breathless and moved nations. It has become very easy for one to create sound that does all this and more, but it has become increasingly hard to control the accidental sound or noise that we as society have inadvertently created and deemed unwanted. Be it the roar of a jet engine or the unnerving hum of a power substation, the study of noise and how to control it has become one of great investment. A vast amount of knowledge has been compiled about noise control. However, with all the knowledge gained thus far, no one person has been able to find a noise control technique to fit all noise situations.

Concerns among the general population, to curb this ever-increasing problem, have given rise to considerable research in the acoustic field. As a result, noise measurement and assessment of its impact upon the individual has been studied by Benton [1] to determine the gap between noise criteria and emerging noise forms. Benton shows attempts made to reduce this gap, and how low frequency noise may stifle endeavors to close the gap. To bridge the gap, increased noise control efforts have been directed towards low frequency noise radiated by structures. In recent publications, low frequency noise radiators were studied, such as power transformers [2], aircraft [3-4], and automobiles [5] which resulted

in a better understanding of acoustic structural behavior. These investigations have also resulted in several noise control techniques, each providing some level of noise control.

1.2 Noise Control Techniques

Many advances in noise control methods have evolved within the past several years. These noise control methods can be categorized by their control mechanisms. Passive, active, and an integration of passive and active to form “hybrid” noise control methods make up these categories.

For many years, passive methods have been used to control noise problems, focusing mainly on the absorption and/or redirection of energy from a source. These methods utilize such mechanisms as structural damping, sound absorptive material, enclosures, and noise barriers. The use of constrained layer damping is a typical structural damping application. In this passive approach, viscoelastic material is applied to the surface of a structure or is placed in between surfaces forming a composite material. Nakra [6] discusses the two basic configurations and how each dissipates vibratory energy. Some particular properties of this passive approach are its ability to only effect certain frequency bands; increasing performance maybe realized with partial coverage of a structure’s surface than full coverage; operation is temperature dependent; and it can be combined with active control. The drawback of this method is the addition of a significant amount of weight. Another commonly implemented passive control method is the application of acoustic foam. However, for acoustic foam to be effective, the necessary thickness to absorb the long acoustic wavelengths at low frequency is not practical for most applications due to space requirement. This also relates to noise barriers and acoustic enclosures where space is again the main constrain for their implementations.

Alternatively, more unique passive methods have evolved with the modal analysis and the understanding of radiation efficiency of planar structures. These methods focus on modal reconstruction to introduce modes shapes that do not couple well with the acoustic mediums, thus producing a poor radiating structure that leads to attenuation of noise at lower frequencies. Work performed by Pierre and Koopman [7] has shown that placement of optimally sized discrete masses to a clamped plate can alter resonant mode shapes into inefficient radiating mode shapes. Performance in sound attenuation from this study indicated sound power reduction of 10 dB is achieved over a 700 Hz band from 150-850 Hz. In addition to discrete masses, passively tuned vibration absorbers (TVAs) have been used to alter the response of structures creating inefficient radiators coupled with motion suppression in some cases. With passive TVAs existing for nearly a century, many design configurations and guidelines have been developed to control both structural vibration and sound radiation. Sun, Jolly, and Norris [8] give helpful information to many of these TVA designs in a thorough overview. The optimum tuning and placement of the TVA(s) is a critical factor for effective cancellation of vibration and noise. For example, Nagaya and Li [9] study the design of electromagnetic TVA. In this work, neural networks are used to obtain the optimal parameters for the absorbers, where the first five structural modes are of concern. It is also found that integration of the sound pressure over the frequency region 0–300 Hz, utilized as a cost function, allows for control of the first five modes with three absorbers. The experimental acoustic power spectrum results show noise reduction of 22.5, 18.9, 12.6, 19.8, and 18.0 dB for the first through fifth modes, respectively. These experimental results compared well with the numerical model.

Hence TVAs and discrete masses have proven to be very useful in vibration and acoustic noise control. However, these passive methods have drawbacks such as the obvious weight increase. Another significant problem to discrete masses and TVAs is their limitation to narrow or tonal frequency disturbances. Furthermore, if TVAs are improperly designed and tuned, transient responses and large shifts in operating disturbance frequencies may cause TVAs to increase vibration level and noise. To this end, Jolly and

Sun [10] study the effects of TVA tuning relative to the critical frequency of a simply supported panel. It is shown that when the TVA is tuned to a critical mode of the panel, reductions result in radiation efficiency near and below the tuning frequency. However, when TVAs are tuned to a mode other than the critical mode of the panel, the radiation efficiency of the panel is increased in the vicinity of the tuning frequency.

The passive methods described here have provide effective attenuation mainly in mid to higher frequency range, but they have not provided sufficient reductions at low frequencies, which is the major concern. This persistent need for low frequency noise control has lead to the investigation of active methods. With the recent advent of the faster processing computer, actively controlled devices have gained great popularity while overcoming some limitations seen by passive methods of noise control; i.e., limited frequency region control. As general terminology, active control techniques add energy to a system via an actuator in attempts to change the behavior of an existing system.

Active Noise Control (ANC) and Active Structural Acoustic Control (ASAC) make up two primary noise control methods developed with active systems. In ANC, sound attenuation is achieved by the destructive interference between pressure waves introduced by secondary acoustic sources (i.e., actuators) and the primary disturbance waves. The error sensors are microphones properly positioned in the acoustic field. For example Salikuddin and Ahuja preformed a study using secondary acoustic sources [11]. In this experimental study, ANC reduced localized interior propeller aircraft cabin noise at 400 Hz by 10 dB. Additional, tests conducted at 1000 Hz showed localized noise reduction of 3 dB, however, accompanied by non-localized noise increase over primary noise levels by 5dB. Also demonstrated is the potential use of this technique to control noise of the first four harmonics of the blade passing frequency, e.g. tonal noise reduction as high as 17 dB. Typically, ANC requires many control transducers and to be effective, the destructive wave field must be reproduced in sufficient time to cancel the primary noise source field, i.e., causality effect [12]. Although, causality is not an issue with tonal disturbances, it is

of paramount importance for broadband disturbances. An approach to alleviate this causality problem is to place the secondary sound sources as close as possible to the disturbance.

Active Structural Acoustic Control (ASAC) method uses actuators integrated within a structure to modify the structural response to minimize the radiated sound. In this approach, the error sensors can be placed in the sound field or on the structure. An example of ASAC is the implementation of adaptive tuned vibration absorbers (ATVAs), which provide a means to overcome the limited frequency range drawbacks [13]. Studies by several authors of piezoelectric transducer actuators have shown promising results for both noise and vibration control [14-17]. The key advantage of these actuators is the small size and small weight added to the structure.

In the last several years, hybrid systems, i.e., a combination of passive and active techniques, have been a topic of major interest. One basic design involves piezoelectric polymer film (PVDF) embedded in porous layers (i.e., acoustic foam) [18]. The design of this hybrid system utilizes the foam for passive absorption of noise at higher frequencies and the PVDF is used as an acoustic actuator to enhance the low-frequency sound absorption of the foam. In this experimental study, a cylindrical foam-PVDF element was mounted near the surface of an oscillating rigid piston mounted in a baffle within an anechoic chamber. Results showed noise reduction of 10 dB in the frequency band of 0-1600 Hz.

A different methodology to low frequency noise abatement consists of lowering the volume velocity by a radiating surface. Previous work on active control has revealed that partitioning a structure or panel into acoustic dipole elements possesses the potential for volume velocity control and, thus, sound reduction. The intent of this concept is to convert a structure from an efficient radiator to a weak radiator. Partitioning a structure's surface

into smaller poor radiating acoustic sources has been accomplished by different active design concepts [19-25]. A study conducted by Johnson and Elliot [19] used an array of active components or “tiles,” applied to the surface of beams and plates to reduce vibration level on the structures and change its radiation efficiency. Each tile uses local vibration or pressure as a reference to control volume velocity. Pierre, Koopman, and Chen studied the active control of speakers imbedded in a composite panel excited with broadband frequencies [20]. The panel of loudspeakers created dipole sources for noise control with emphasis toward uses in enclosed spaces, such as airplane and helicopter cabins. Results from this study found 9 dB of noise attenuation for a frequency band of 200-260 Hz. Unfortunately, the power requirement, additional mass, unreliability, complexity, and high cost associated with active control systems has considerably limited its use in the marketplace. Thus, there is still a need for effective and practical low frequency noise control approaches.

The purely passive method for volume velocity control of a radiating structure using a weak radiating cell (WRC) concept has been recently developed and experimentally verified on a simple piston structure [26]. The weak radiating cell is a mechanical device that converts the motion of the vibrating structure into an inefficient radiating acoustic dipole source, which leads to the passive reduction of low frequency sound. Since the approach is passive, it eliminates many of the adverse effects introduced by active control. In previous work by Ross and Burdisso [26], it was suggested that applying an array of weak radiating cells to a more complex structure partitioned into small areas could minimize the radiation from the structure. This concept was experimentally investigated by implementing an array of weak radiating cells to a vibrating plate [27]. The plate was excited with a shaker driven with white noise in the 0-1600 Hz band. The results show an overall sound power level reduction of 10.2 dB in the 100-1600 Hz range as well as reduction of up to 25 dB at discrete frequencies. This demonstrated the effectiveness and potential of the approach.

The objective of this thesis is to accrue knowledge of the physical noise control mechanisms associated with the low frequency passive noise control device referred to as weak radiating cell (WRC). To accomplish this, analytical models of the passive acoustic treatment, WRC, are developed for noise control study. The WRCs are applied as acoustic treatment to two types of radiating structures (i) a simply supported finite beam and (ii) a simply supported finite plate. The response of these structures is modeled using modal expansion. All acoustic responses are then obtained through numerical integration. In addition, a wavenumber transform approach is used to model the WRC treatment implemented on an infinite two-dimensional (2D) plate system. The main advantage of this model is that both the structure and acoustic responses are obtained in closed form. This results in a very effective and simple modeling technique to investigate advanced concepts.

The first analytical model of a simply supported beam model is developed to gain insight into the noise control mechanism of the WRC. Once establishing a firm understanding of the modal response of the treated system, acoustic relations are investigated. Connections between the treated system response and acoustic relations bridge the gap to better understand the noise control mechanisms. Additionally, the beam-WRC model is used to study methods for improvement of the acoustic performance of the WRC system. Lastly, a wavenumber transform method provides another interpretation of the treated system response and associated noise reduction created by the WRCs. In general, this method of analysis associates sound energy from individual wavenumber components of the normal velocity distribution of any planer structure in an infinite baffle. A model of a simple supported plate is developed allowing investigation of more practical implementations. Results from this model are also compared to the experimental validation presented by Ross and Burdisso [27]. In addition to the comparison, select model parameters relative to the experimental setup are modified to enhance the noise control presented by the WRCs. To this end, a wavenumber analysis model is developed for an infinite 2D plate treated with WRCs. This model is used to study the pure acoustic effects of the treated structure radiating at a particular wavenumber with a given frequency.

1.3 Thesis Organization

In Chapter 2, the basic elements of the acoustic relationships that define volume velocity and its role in the noise control mechanism of the WRC are presented. The volume velocity concept is further established by applying the acoustic relationships to a simple piston model.

Following this, a 2-degree of freedom (dof) mathematical model of the WRC applied as treatment to a simple supported beam is developed in Chapter 3. The model is used to explore the mechanical and acoustic effects produced by the WRC. The model is also used to investigate methods to improve the noise attenuation characteristics related to the WRC. Lastly, wavenumber transform equations are developed to foster insight into the WRC behavior.

In Chapter 4, a model is developed of WRCs applied to a simple supported plate. Each cell is modeled as a 3-dof system. For comparison purposes, the experimental test parameters are incorporated and key results by Ross and Burdisso [27] are reproduced. Results from the model configured with similar parameters are then compared to the experimental results. Examination of the results indicates the model provides a reasonable match to the experimental results, and hence a good tool for practical analytical studies. With knowledge obtained from the simple supported beam model regarding improved noise attenuation methods, the plate model is then configured similarly in an attempt to improve on the experimental configuration.

A different modeling technique is presented in Chapter 5 that provides closed form mathematical structural and acoustic solutions of an infinite 2D plate treated with WRCs. The radiated acoustic power is developed from the intensity field at the surface of the structure by way of wavenumber transform. In addition, the sound intensity vector field is computed to illustrate the acoustic energy flow patterns. This unique model provides fast results compared to previous modeling techniques.

Chapter 6 includes a summary of the work contained in this thesis and the main conclusions about the WRCs as a noise control treatment. Finally, recommendations are given as guidance to future research directions.