CHAPTER 6
PRACTICAL CONSIDERATIONS AND LIMITATIONS

6.1 Mode Shape Orientation

For a closed cylinder, the orientation of the structural and acoustic modes shapes in the circumferential direction is determined by the excitation. Since the actuator in this analysis is located at $\theta = 0^\circ$, the mode shapes are aligned about $\theta = 0^\circ$. For the fairing, the acoustic disturbance is provided from the reflection of sound from the launch pad or by the induced vibration caused by the turbulent flow passing over the fairing during flight. In either case, the acoustic loading exhibits no particular orientation. This implies that redundant actuators are necessary because some of the actuators will be placed at nodes of the structural modes. For example, if a disturbance excites a cylinder such that its motion is dominated by the (2,1) mode, oriented at $\theta = 0^\circ$, an actuator located at $\theta = 0^\circ$ can control the cylinder motion. If however the same disturbance is rotated by 45°, the original actuator located at $\theta = 0^\circ$ will have little or no authority to control the disturbance. Therefore a redundant actuator is required at $\theta = 45^\circ$ to control the rotated disturbance. Now if both actuators are used, they will still have little or no control authority for a disturbance that excites the (4,1) mode oriented at $\theta = 22.5^\circ$. As the number of modes to be controlled increases, so shall the number of actuators required.

6.2 Applications to Larger Fairings

The analysis presented in this work is performed on a Minotaur fairing, which represents a medium sized fairing. For larger payload fairings, the authority of the control system may be insufficient for several reasons. As the size of the cavity increases, there exists a larger surface area for acoustic energy to penetrate through the fairing skin. Also, since the size of the cavity is increased and the energy density of the enclosed acoustic field remains essentially the same, there exists more acoustic energy to control. Lastly, the ability of an actuator or acoustic control source to generate sound inside a cavity decreases as the size of the cavity increases. This implies if a control system is marginally capable of controlling the sound in a given sized fairing, it will have more difficulty in controlling the sound in larger sized fairings due to the increased energy requirements.

6.3 Control Issues

The acoustic loading that is imparted on the fairing is caused by the reflection of sound off of the launch pad during liftoff or by the turbulent flow passing over the fairing, inducing vibration in the fairing skin. In many active acoustic control schemes a signal which is correlated with the disturbance can be used to assist in controlling the sound or vibration. For the fairing problem, a reference signal correlated with the disturbance does not exist. Therefore the use of feedforward control is not practical. Global structural control is also extremely difficult because of the complexity and lack of a comprehensive structural-acoustic model for the fairing.

6.4 PZT Actuator Non-linearity

In the linear region of a PZT actuator, the force or displacement induced by the actuator is proportional to the applied electric field. In this analysis the PZT actuator is assumed to operate linearly until its de-poling voltage (300 kV/m for PSI-5H-S2). In reality the force or displacement response of the actuator exhibits non-linear behavior and hysteresis at higher actuation levels (above ~100 kV/m). Including this non-linearity in the present analysis will reduce the overall performance of the PZT actuator. This implies that the structural response predicted by the impedance model will be larger than the actual response for a SS cylinder. This also means that the model's prediction of the sound generated by the PZT actuator within the cylinder will be higher than the actual acoustic response.

The electrical capacitance of a PZT actuator is usually defined by its free strain value. Since the actuator is mounted to a structure that has mechanical resonant frequencies, there will be some effect on the actuator's capacitance and electrical impedance. The PZT actuator operation is based on the converse piezoelectric effect. Since the actuation and sensing constitutive equations are coupled, the PZT material will also generate a charge across the electrodes when strained. It is assumed that the changes in capacitance and charge generated due to the direct piezoelectric effect are small and can be neglected. Also, any internal resistance of the PZT actuator is considered small compared to the capacitive impedance of the actuator.

The analysis presented in chapter 5 assumes that the superposition principal applies when multiple actuators are used. The model is based on a pair of co-located actuators operating in phase and can essentially be considered a single actuator. When multiple actuators are used, the response of the cylinder is assumed to increase proportionally. However, since the in-plane strain also increases, the actuator's authority will decrease because the local impedance of the cylinder is reduced. This implies that the model will underestimate the number of actuators required in order to obtain a required structural response, when a significant number of actuators are used.

6.5 PZT Actuator Tensile Properties

Another drawback of PZT actuators that is not directly addressed in this work, is their material strength. PZT actuators lack the ability to withstand significant tensile loading. The dynamic tensile strength of the actuator analyzed (PSI-5H-S2) is approximately 16 MPa. The tensile strength for aluminum is approximately 412 MPa. This implies that aluminum is approximately 25 times stronger in tension than a PZT actuator of equivalent dimension. In practice, common PZT actuators are extremely brittle and commonly crack during fabrication or while being used to excite a structure at high levels. Other types of piezoelectric based actuators may be a potential solution to this problem. One product called, "QuickPack" (Active Control eXperts; Cambridge, MA) packages piezoelectric materials in a protective skin that is resistant to microcracks during operation. If PZT actuators are to be practically implemented, the challenges created due to their brittle behavior must be overcome.

6.6 Single or Co-located Actuators

The impedance model is derived for a pair of co-located PZT actuators operating in-phase. The simulations performed for the various cases, described in section 5.2.6, are based on a single actuator embedded at the neutral axis. This is done because mounting PZT actuators on the outer surface of a fairing is unrealistic. Therefore the actuation of a pair of co-located actuators needs to be equated to a single actuator. If the area of an actuator remains fixed and only the thickness and the applied voltage is altered, it can be shown that two actuators half as thick, operating at half the applied voltage, will provide equivalent actuation. However, the two actuators will consume twice the current. If an amplifier is current limited, it is better to use a single, thick PZT actuator. Likewise, if an amplifier is voltage limited, it is better to use two thinner PZT actuators. Usually electrical amplifiers have current limitations, and so this analysis is performed for a single PZT actuator in order to keep the calculated currents as low as possible.

6.7 Fairing and Cylinder Modal Density

In this simulation the fairing is modeled as a SS cylinder. Below 400 Hz the cylinder has approximately 30 structural shell modes, with the first shell mode frequency occurring at 75Hz. The axial and bending modes of the cylinder are not considered in this analysis. For the STARS fairing, there are nearly 300 structural modes and 73 acoustic modes up to 500 Hz (Glaese and Anderson, 1999). It is likely that some of these non-shell structural modes will couple well with the internal acoustic field of the fairing. This is one significant aspect in which the model of the cylinder differs from the actual fairing. For the cylinder analyzed, there are 76 acoustic modes below 500 Hz. This acoustic modal density is approximately the same as compared to the STARS (similar in size to Minotaur) fairing.

6.8 Potential Sources of Error

The intent of this work is to determine the acoustic authority of a PZT actuator as applied to an actual payload fairing. There are several aspects of the structural and acoustic model that may provide potential sources of error. The cylinder and the actual fairing have different geometry and so the structural and acoustic modes of each structure will differ. Also, in this analysis only the shell modes of the cylinder are considered. The fairing response will contain bending and axial motion that will undoubtedly couple into the internal acoustic field. This additional motion is neglected in this analysis. However, if it were included there would exist more modes to control and so the current requirements of the actuator would increase over that which is presently estimated.

For the structural model the loss factor is determined from an experiment performed on a composite grid stiffened plate. The actual damping within the fairing may differ and will therefore affect the magnitude of the structural response. In determining the number of required actuators and current consumption, a very low structural damping value was chosen ($\eta = 0.007$). This will produce a structural response that is likely to be higher than the actual value. Since the acoustic field within the cylinder is dominated by the acoustic modes and not the structural modes, large deviations in the structural model are not as sensitive to the overall acoustic response.

The acoustic model presented in this work assumes there is no structural-acoustic interaction for the cylinder. The interior acoustic response of the cylinder is expressed in terms of the rigid walled acoustic modes for the cylinder. In other words the shell vibration is independent of the interior acoustic loading. This approximation is generally valid if the acoustic medium is air and the sound pressure levels are less than 130 dB. If the structural-acoustic interaction is to be included, the net effect will reduce the vibration of the cylinder and the interior sound levels. This implies that the structural and acoustic model will over predict the structural response and the internal acoustic response of the cylinder, particularly for SPLs in excess of 130 dB.

The acoustic loss factor in this simulation ($\eta_a = 0.001$) is determined from the experiment described in chapter 4. The value is assumed to be constant over the frequency range of interest. It is also assumed to be valid for a large scale cylinder. The acoustic loss factor used in this analysis is based on a small aluminum cylinder with no acoustic damping treatments. In the low frequency range, for a payload fairing, the acoustic blankets have little sound absorbing ability. It is assumed that the loss factor used will be reasonably close to the loss factor for the environment within an actual fairing. As was shown in chapter 4, the acoustic loss factor only affects the acoustic response near an acoustic resonance. Even if the actual acoustic loss factor deviates from the value used by a large factor, the results away from the acoustic resonance will still be valid.

6.9 Convergence Test

Because the acoustic model is based on a boundary element formulation, a convergence check needs to be performed in order to have confidence in the model. The acoustic analysis numerically integrates the K-H integral based on the number of spatial accelerance points calculated using the impedance model. To compute the internal acoustic response for the cylinder as described in chapter 4, 12 axial elements and 36 circumferential elements are used. Based on the results obtained from the experiment, this resolution is satisfactory. However, for the cylinder used to model the Minotaur fairing, the structural reverberant modal indices are higher, and so more elements are required. For the analysis performed in chapter 5, 15 axial elements and 45 circumferential elements are used. A duplicate analysis is performed for Case 1 of chapter 5, using 18 axial and 60 circumferential elements. Both simulations produced virtually identical results. It can therefore be concluded that the element resolution is sufficient.