

## **CHAPTER 7**

### **CONCLUSIONS**

The focus of this work was motivated to provide an answer to the following questions, or at least provide significant insight to the possible answers:

Does the PZT actuator have the authority to control PF internal SPLs?

If it does, will the electrical current or power draw be excessive for the launch vehicle?

This chapter will directly address these questions and review the significant findings of this work.

#### **7.1 Structural Model**

The structural response of a simply-supported (SS) cylinder excited by a pair of co-located piezoelectric (PZT) actuators was presented. The theoretical formulation of Lalande's impedance model of a PZT actuator exciting a SS cylinder was reviewed. The creation of a SS boundary condition on an actual cylinder was also described along with the measured dynamic properties of the cylinder. The results indicate that the relative magnitude of the predicted response is similar to the measured response for the cylinder tested (within half an order of magnitude). The model is able to predict the general modal behavior of the cylinder although the natural frequencies of some modes are shifted. These frequency shifts are likely due to the interaction between the cylinder and the endplate's second and third modes. For a complex structure, like a cylinder, some inconsistent results can be expected. The analytical natural frequencies compared to those predicted by finite element analysis are in agreement. Also, the operating shape of the cylinder predicted by the model at a particular natural frequency is similar to the corresponding dominant mode shape. This is indicative that the model is valid. Even though the frequencies of some modes are shifted, the dominant behavior of the cylinder is predicted by the model and the relative displacement magnitudes are reasonably close. For the acoustic analysis performed in this work, the exact location of the resonant frequencies is not critical. Since it is the magnitude and spatial displacement pattern of the operating shape that is more important to this overall analysis, the impedance model is acceptable. The structural model was used to predict the structural response of a large scale cylinder which emulates a rocket payload fairing (PF).

#### **7.2 Acoustic Model**

The calculation of the internal acoustic response of a simply-supported (SS) cylinder has also been described. The model is based on a boundary element formulation of the Kirchoff-Helmholtz integral. In order to verify the boundary element model, an analytical solution to the acoustic response of a cylinder vibrating with a single mode structural vibration was also

derived. The results from the analytical solution and the boundary element model are essentially identical.

The acoustic boundary element model was also verified experimentally using a simply-supported cylinder with closed ends. An experiment was performed to measure the acoustic response within a SS cylinder for a given structural excitation. The spatial structural acceleration of the cylinder was measured (using a roving accelerometer) and used with the numerical boundary element model to predict the acoustic response of the SS cylinder. The predicted and experimental results were compared and an acoustic loss factor was determined for the aluminum cylinder interior space. The acoustic loss factor influences the magnitude of the acoustic response near the acoustic resonances while the changes in the loss factor have little effect away from an acoustic resonance. This is also found to be true at the acoustic peaks controlled by the cylinder structural resonances.

It was found that the results predicted by the model and the experimental results are in close agreement. The model is able to predict the acoustic behavior within the cylinder for various positions and frequencies. Most of the resonances and anti-resonances are predicted with only slight shifts in frequency. This is indicative that the acoustic model is valid. It should be reiterated that the motion of the structure is assumed to be uncoupled with the internal acoustics, and so the structural-acoustic interaction is not considered in this analysis.

### **7.3 Simulations**

Several simulations were performed on a large scale cylinder that emulates a Minotaur payload fairing. Since the exact stiffness and damping of the fairing is not known, a variety of test cases were performed. A PZT actuator is used to excite the cylinder at a maximum voltage level that does not exceed the actuator's de-poling electric field. The internal acoustic response of the actuated cylinder is examined at a location that represents essentially the highest internal acoustic SPL. The acoustic levels were investigated for the various test cases between 35 and 400 Hz.

It was found that the changes in cylinder parameters (stiffness and material density) from case to case do not have a large effect on the magnitude of the cylinder structural response. The significant changes from case to case appear in the natural frequencies of the cylinder. Likewise the interior acoustic response is not greatly affected by changes to the structure.

As the applied voltage increases linearly, the internal SPL varies logarithmically. If the applied voltage is doubled, the internal SPL increases by ~6 dB. Likewise to achieve a ~20 dB increase in the internal sound field, it is necessary to increase the structural response ten times. This would require ten times the applied voltage or ten times the number of actuators. This behavior is clearly a limiting factor in using a PZT actuator to generate high internal SPLs.

Significant reductions in the structural response due to increased damping do not show a similar reduction in the acoustic SPLs for the cylinder. The sound levels at the acoustic resonant frequencies are essentially unaffected by the significant increase in structural damping. The

acoustic levels at the structural resonant frequencies are mildly reduced due to the reduction in the structural response.

The interior acoustic response of the cylinder is dominated by the acoustic modes and therefore, significant reductions in the overall interior acoustic levels will not be achieved if only the structural resonances are controlled.

The model indicates that the maximum acoustic levels generated by the baseline PZT actuator are sufficient at the higher frequency range but are not commensurate with the levels found in a typical fairing in the lower frequency range (below ~200 Hz). Since the baseline actuator's applied voltage can not be increased, additional actuators are required in order to increase the response of the cylinder at some of the lower frequencies. The baseline actuator is clearly better at generating sound within the cylinder as the frequency increases. This implies that more actuators will be required to control the lower frequency modes than the higher frequency modes.

As the actuation frequency is reduced, the number of actuators required to generate SPLs commensurate to the acoustic levels found in the fairing increases to impractical values. Below approximately 100 Hz, the current demands reach levels that are extremely difficult to achieve with a practical system. The results of this work imply that PZT actuators do not have the authority to control the payload fairing internal acoustics below ~100 Hz. It should be noted that considering the structural-acoustic interaction may affect the results of this analysis and yield different conclusions.

## **7.4 Future Work**

Many approximations were made in this work to facilitate the analysis. In this analysis the fairing was represented by a simply-supported cylinder. The cylinder and the actual fairing have different geometry and so the structural and acoustic modes of each structure will differ. Clearly this is a first-order approximation of the actual system. An actual payload fairing is a complex structure and presently a robust model of such a system does not exist. More work needs to be done in modeling the payload fairing in order to gain an understanding of the structure's dynamic and acoustic properties.

Only the shell modes of the cylinder are considered herein. The fairing response will contain bending and axial motion that will undoubtedly couple into the internal acoustic field. This additional motion is neglected in the present analysis. A more comprehensive analysis using a cylinder would have a simply-supported boundary condition at one end and a free boundary condition at the other. For this system, the bending and axial effects could be included.

The acoustic model presented in this work assumes there is no structural-acoustic interaction (SAI) 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. A more sophisticated model would include

the SAI and may be more accurate. Additional work needs to be done in determining the effect of the SAI for the actual fairing. For the acoustic environment experienced during launch, is the SAI significant, and at what levels does it become significant? This problem needs to be further explored.

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. The acoustic modes for the fairing are strongly dependent on the geometry of the cavity, payload, and orientation of the loading. Not knowing the internal spatial acoustic mode shape or the alignment of these modes makes controlling the interior acoustic space difficult. These effects need to be further investigated.

PZT actuators lack the ability to withstand significant tensile loading. If PZT actuators are to be practically implemented, the challenges created due to their brittle behavior must also be overcome.

The use of PZT actuators in active structural control is desirable because they can be easily mounted or embedded onto structures, require little space, and have a high actuating bandwidth. This analysis indicates that the current demands required by PZT actuators reach levels that are extremely difficult to achieve with a practical system. This is partly caused because of the broadband nature of the fairing acoustical problem. The existing amplifiers required to excite PZT actuators in various broadband applications need to be improved. Some possible solutions may include using power-factor correction methods or advanced switching power supplies.