Vibroacoustic Analysis and Experimental Validation of the Structural Responses of NASA Mars Exploration Rover Spacecraft Due to Acoustic Launch Load

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1. ABSTRACT

Structural responses of a spacecraft during liftoff are dominated by the intense acoustic pressure field impinging on the exterior of the launch vehicle. Statistical Energy Analysis (SEA) model of the NASA Mars Exploration Rover (MER) spacecraft has been developed and the SEA model was analyzed to predict the vibroacoustic responses of the spacecraft under the diffuse acoustic loading condition. The MER spacecraft was subjected to the broadband acoustic excitation in JPL's reverberant chamber simulating the acoustic environment during launch. The measured structural responses at various locations of the spacecraft have been correlated with the SEA results. Resonant response of the Transverse Impulse Rocket System (TIRS) motor mounted on the MER spacecraft has been analytically predicted using the response of the surrounding panel obtained from the SEA modeling. Comparisons have been made between the SEA responses and the acoustic test data and good agreements have been found at various locations of the spacecraft.

2. INTRODUCTION

Jet Propulsion Laboratory (JPL) is NASA's lead center for robotic exploration of the solar system. JPL's missions to Mars began in the early 1960's and recently in 1997, JPL sent a remotely controlled rover to Mars in a spacecraft named Pathfinder. Mars Pathfinder not only accomplished the demonstration of a way to deliver an instrumented lander and a free ranging robotic rover to the surface of Mars but also returned an unprecedented amount of data and outlived its primary design life. JPL is in charge of the current and future Mars missions including MER and Mars Science Laboratory programs. Two identical spacecrafts and rovers have been built for the MER program. The first MER spacecraft will be launched in May 2003. The second MER spacecraft is scheduled to be launched in June 2003. Each spacecraft contains a free ranging rover that will be remotely controlled from JPL to investigate the possibility of the existence of water on Mars.

The mission to Mars consists of various phases of flight sequences including launch, cruise, entry, descent and landing. Definition of dynamics specifications of a spacecraft during the launch condition is the most critical because the spacecraft experiences high frequency acoustic noise as well as low frequency structural-borne random vibrations originating from the launch vehicle engines and motors[1]. This paper deals with a mathematical prediction model based on SEA modeling to predict vibroacoustic responses at various locations of the MER spacecraft generated by the high frequency acoustic noise during the launch condition.

To investigate vibroacoustic responses of a complicated dynamic system such as MER spacecraft is challenging. The more familiar numerical methods such as Finite Element Method (FEM) or Boundary Element Method (BEM) are not efficient or accurate in high frequencies or in modally dense systems. However, SEA can be more useful to predict system responses in high frequencies because the statistical nature of the theory does not require a higher degrees of freedom model[2]. Numerous papers have been published to document the applications of the SEA theory to model various products. Especially, during the last 5 years, SEA applications have been extended to Boeing's 737 aircraft[3] and Raytheon's Premier I small business jet aircraft[4] cabin interior noise predictions. Recently, SEA modeling of the NASA's Mars Pathfinder spacecraft has been accomplished[5].

In the following discussions, SEA model of the NASA's MER spacecraft is explained. Next, model validation is addressed. Vibroacoustic responses of the MER spacecraft obtained from the SEA modeling are correlated with the acoustic test data.

3. MER AEROSHELL SEA MODEL

Figure 3-1 shows MER spacecraft consisting of Aeroshell, Cruise Stage, Lander and Rover. Aeroshell consists of Heatshield and Backshell. The MER SEA model was developed based on the FEM model of the MER Aeroshell. The large surface area (approximately 13.10 m^2) and relatively light (approximately 123.30 Kg) MER Aeroshell is sensitive to the acoustic input. The acoustic Sound Pressure Level (SPL) inside the payload section of the Boeing's Delta II launch vehicle is 142.1 dB(A). The required SPL input for the qualification of the MER spacecraft is 145.1 dB(A) which includes extra 3 dB(A) margin. In the current SEA modeling, the acoustic input was modeled as a diffuse acoustic field with the magnitude of 145.1 dB(A) impinging on the surface of the Aeroshell.

The current MER SEA model does not contain Cruise Stage, Lander or Rover. In previous SEA modeling of Mars Pathfinder spacecraft, it has been analyzed that the SPL inside the Aeroshell was approximately 10 or 15 dBs lower than the SPL input. Since there has not been a major change in Aeroshell design between the Pathfinder and MER models, it is expected that the SPL inside the MER Aeroshell would be at least 10 or 15 dBs lower than the input. Also, Lander or Rover does not contain structural assemblies with large surface areas, which are sensitive to the acoustic input. In order to correctly predict the vibroacoustic responses of the Lander and Rover systems, further investigations are necessary; *for example*, 1. Correctly predict the SPL inside the Aeroshell and 2. Correctly model the coupling and transmission paths between the Lander and Rover systems.

Cruise Stage contains large panels of solar arrays, which are sensitive to the acoustic loading. Cruise Stage has not been a part of the current SEA modeling. The acoustic power flow from the Cruise Stage to the Aeroshell is minimal. The solar arrays of the Cruise Stage are largely loosely connected to the ribs of the Cruise Stage causing the isolation of the vibrations to the ribs. Furthermore, fundamental mode of the solar arrays due to the acoustic input is higher than 300 Hz, which would not resonate the ribs of the Cruise Stage. Solar panels of the Cruise Stage have been separately analyzed to predict the vibroacoustic responses. SEA modeling of the Cruise Stage is not presented herein. Figure 3-2 shows MER Aeroshell SEA model developed in AutoSEA Version 2.2. AutoSEA Version 2.2 is a SEA software package developed by the Vibro-Acoustic Sciences.

The MER Aeroshell SEA model includes approximately 61 structural subsystems. Approximately half the weight of the spacecraft is non-structural. Non-structural masses have been incorporated into the structural subsystems by calculating effective densities of the structural subsystems as shown in Equation 3-1. The spacecraft is mainly built with Honeycomb composite materials. Structural damping loss factors of the composite materials are unknown, however in this SEA study, damping loss factor of 1% was used for all of the structural subsystems. M and ρ represent mass and density respectively.

$$\rho_{new} = \left[\frac{M_{structural} + M_{non-structural}}{M_{structural}} \right] \cdot \rho_{structural} \tag{3-1}$$

4. MER SPACECRAFT REVERBERANT ACOUSTIC TEST

Fully assembled complete MER spacecraft was subjected to the broadband acoustic input in JPL's reverberant chamber. Figure 4-1 shows MER spacecraft located inside the acoustic chamber. Total 128 channels of accelerometers were placed at various locations of the MER spacecraft to measure the structural responses under the acoustic loading condition. Figure 4-2 shows measured SPL inside the acoustic chamber compared with the MER acoustic input requirement. SPL was controlled up to 1000 Hz. The measured SPL is in a good agreement with the MER acoustic input requirement up to 1000 Hz. Figure 4-2 also shows tolerance band of the SPL input, which was +/- 3 dBs. Absorption in high frequencies after 1000 Hz can be controlled with, *for example*, sound absorbing materials.

5. SEA RESULTS AND CORRELATION WITH ACOUSTIC TEST DATA

The obtained structural responses measured at various locations of the spacecraft have been correlated with the SEA results. The measured structural responses of the Heatshield were averaged and compared with the result obtained from the SEA modeling in Figure 5-1. The SEA response is mainly in accordance with the test data, however the SEA model over-predicted the response up to 500 Hz. The Heatshield is coated with a thermal protective layer, which would decrease the structural responses. The SEA model predicted a fundamental ring frequency of the Heatshield in low frequencies between 100 and 200 Hz. However, in reality, the measured structural resonance is usually lower than the mathematical response. Third, modal density of the SEA model in low frequencies is not high enough. Lastly, the discrepancy could be also related to the incorrect power calculation, which is determined by the diffuse acoustic spectrum and the joint acceptance of the structural subsystems. The SEA model was able to predict the response reasonably well after 500 Hz.

Figure 5-2 shows measured average structural response of the Backshell compared with the response obtained from the SEA model. The SEA response is in a good agreement with the test data, except in lower frequencies, *for example*, less than 300 Hz. Another reason of discrepancy could be related to the formulation of radiation efficiencies in SEA theory. Approximately half of the MER Aeroshell's weight is non-structural and it is known that classic SEA radiation efficiencies of the mass loaded panels are not efficient in low frequencies. Several methods have been proposed to increase the accuracy of the structural responses in low frequencies. Examples include NASA Lewis / VAPEPS Path 49 method[6].

Figure 5-3 shows TIRS motor located on the Backshell. Resonant response of the TIRS motor was analytically predicted and compared with the test data in Figure 5-4. The TIRS motor weighs 2.74 Kg. The motor was assumed as a single degree of freedom system with the local panel vibration input as shown in Equation 5-1 (*V* is velocity, *Z* is impedance, *i* is imaginary constant, *M* is mass and *omega* is angular frequency). The analytical response of the TIRS motor shows a good agreement with the test data at the resonance (approximately 125 Hz) and up to 2000 Hz.

$$V_{TIRS}^{\;2} = \left| \frac{Z_{Backshell}^{\infty}}{Z_{Backshell}^{\infty} + i\omega M_{TIRS}} \right|^2 \cdot V_{Backshell}^{\;2} \qquad (5\text{-}1)$$

6. CONCUSIONS

MER Aeroshell SEA model has been developed. Diffuse acoustic loading has been applied on the SEA model to simulate the reverberant acoustic input. Predicted vibroacoustic responses of the Heatshield and Backshell have been correlated with the JPL's acoustic test data. Resonant response of the TIRS motor has been predicted with the impedance relationship of the point mass and the local panel vibration input.

The SEA responses were found to be mainly in accordance with the test data. The SEA model over-predicted structural responses in relatively low frequencies. Radiation efficiencies should be revisited to improve the SEA responses in low frequencies. Further model refinement and validation should also be conducted to improve the SEA results.

7. ACKNOWLEDGEMENTS

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REFERENCES

[1]"Dynamics Environmental Criteria Handbook," *NASA Technical Handbook NASA-HDBK-7005.*
[2] Richard H Lyon and Richard G. DeJong, *Theory and Application of Statistical Energy Analysis 2nd Edition* (Butterworth Heinemann).
[3] J. S. Alex Lin, "Airplane Interior Noise Modeling Using Statistical Energy Analysis Approach," *AIAA 99-27867, AIAA-99-1903.*
[4] Ho-Jin Hwang, Dayton Hartley, Ronald G. Hund, John F. Wilby, "Raytheon Premier I Interior Cabin Noise Modeling Using Statistical Energy Analysis," *Proceedings of the First International AutoSEA Users Conference*, July 27-28 2000.
[5] Ho-Jin Hwang, "Prediction and Validation of High Frequency Vibration Responses of NASA Mars Pathfinder Spacecraft Due to Acoustic Launch Load Using Statistical Energy Analysis," *Proceedings of ESTECH 2002 - the IEST 48th Annual Technical Meeting Conference*, April 28 – May 1 2002.
[6] Mark E. McNelis, "Extension of SEA Treatment of Radiation Efficient to Low Frequency," *AutoSEA Aero/SEA Technical Exchange Meeting*, March 28 2001.

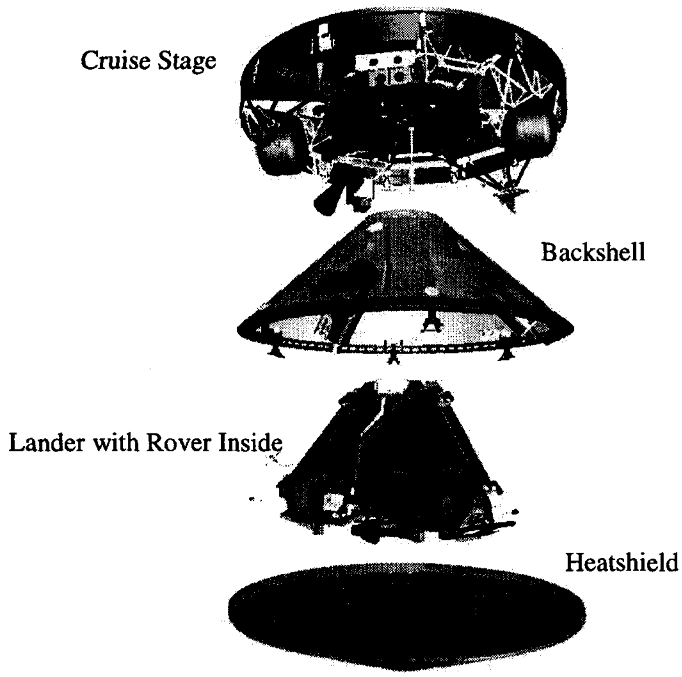

Figure 3-1: Complete MER Spacecraft Model – The MER spacecraft consists of Aeroshell, Cruise Stage, Lander and Rover. Aeroshell consists of Heatshield and Backshell. Rover is located inside the Lander.

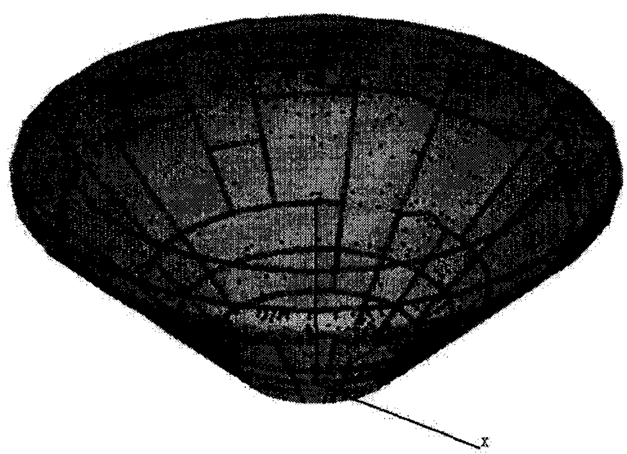

Figure 3-2: SEA Model of the MER Aeroshell – The MER Aeroshell was modeled with 61 structural subsystems. Excitation is diffuse acoustic loading impinging on the Aeroshell. Red lines are line junctions. Blue dots are grid points imported from the Finite Element Model.

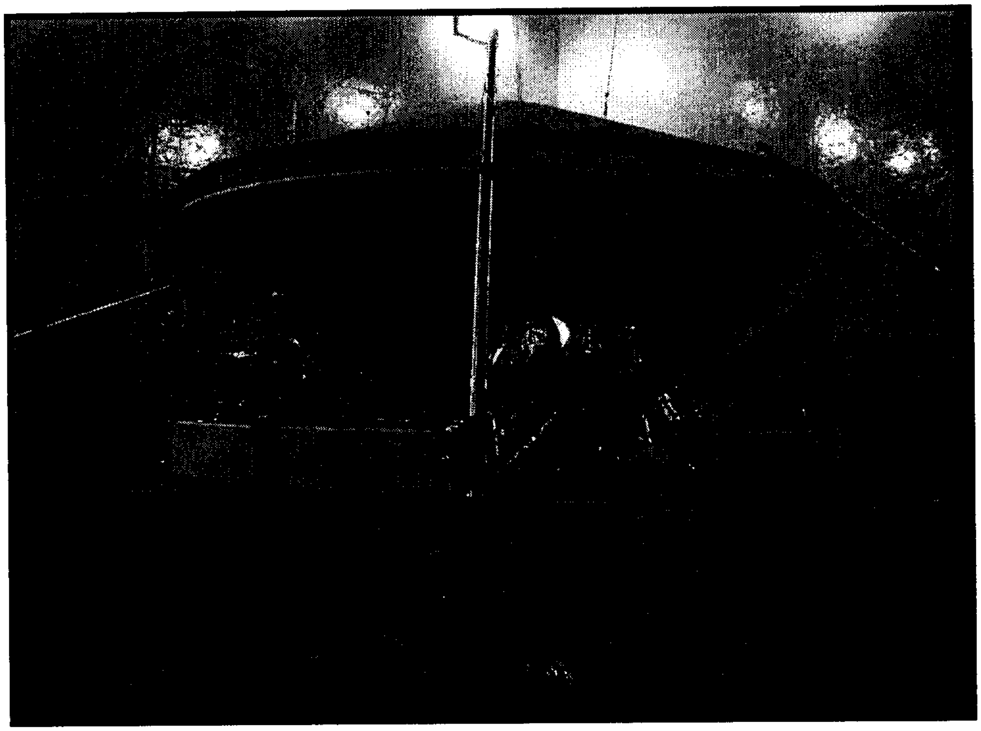

Figure 4-1: MER Spacecraft in JPL's Reverberation Chamber – The first MER spacecraft underwent an acoustic test for 60 seconds at the qualification level of 145.1 dB(A). The spacecraft was mounted on the Boeing supplied Payload Attachment Fitting (PAF).

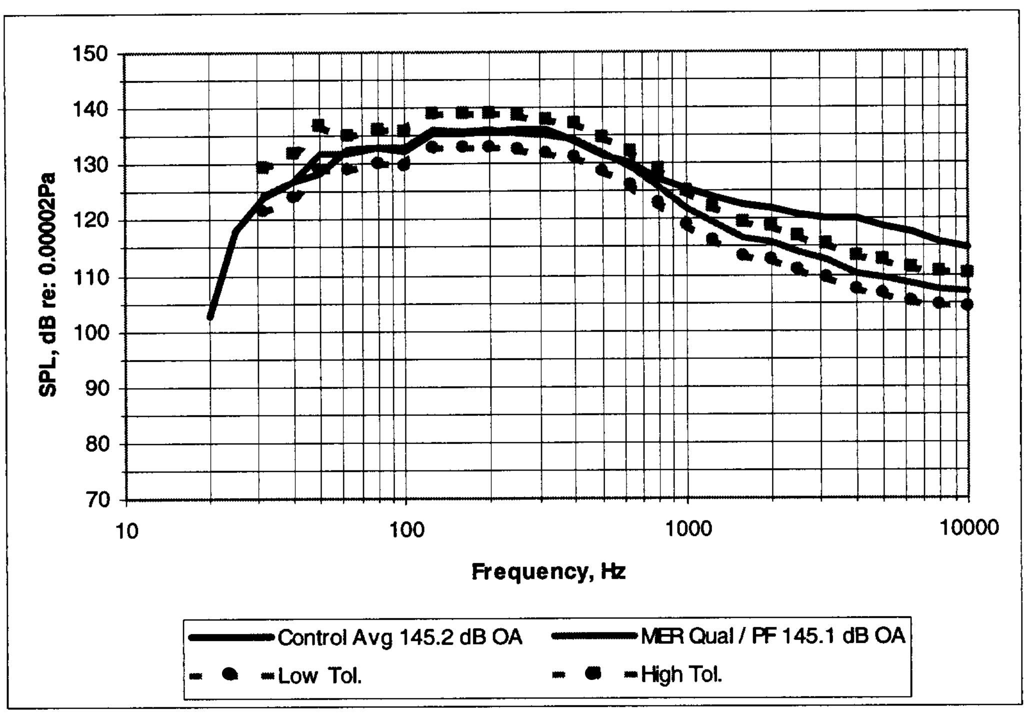

Figure 4-2: SPL Measured during the Reverberant Acoustic Test – The measured SPL during the acoustic test shows a good agreement with the qualification input profile. The SPL was only controlled up to 1000 Hz.

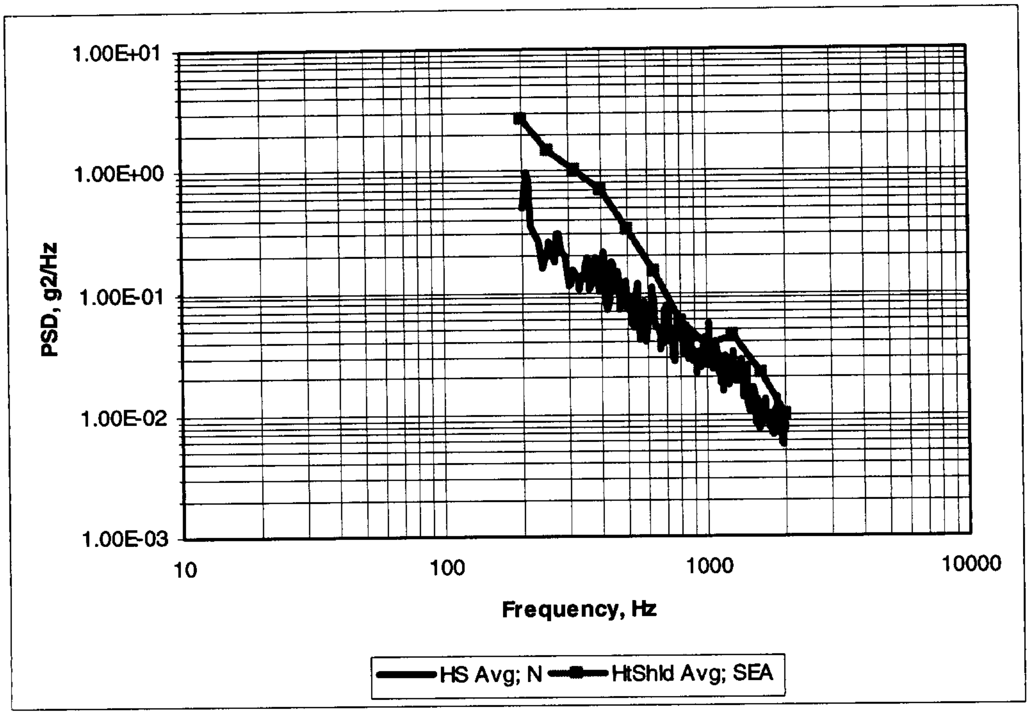

Figure 5-1: Vibroacoustic Response of the Heatshield Obtained from the SEA Modeling – The SEA response is compared with the acoustic test data. The SEA response is in a good agreement with the test data after approximately 500 Hz.

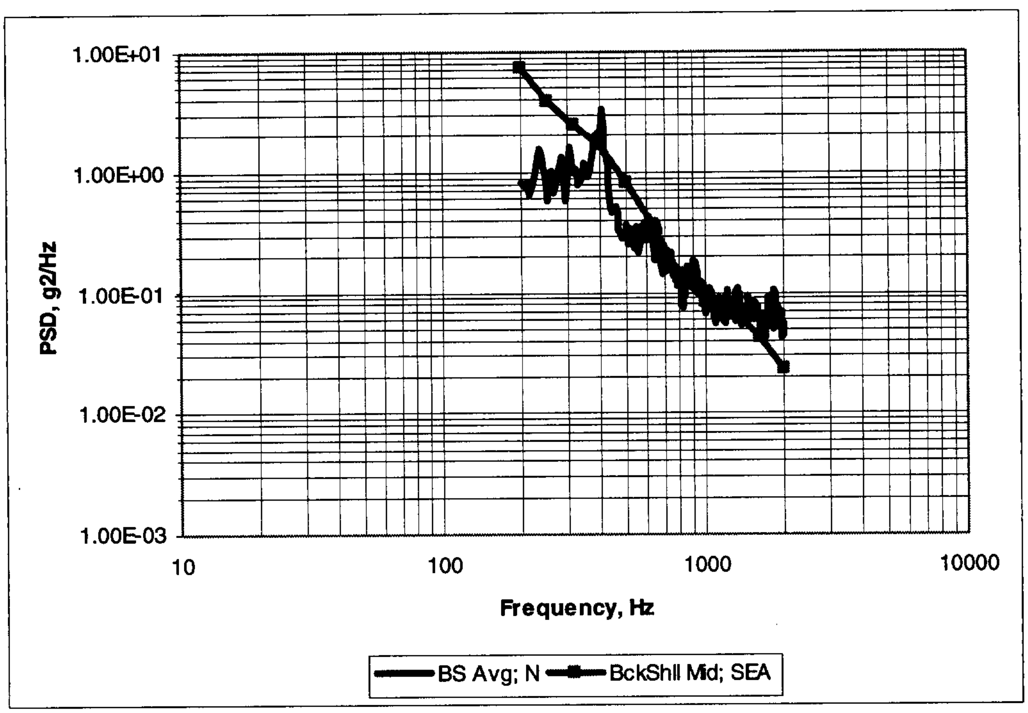

Figure 5-2: Vibroacoustic Response of the Backshell Obtained from the SEA Modeling – The SEA response is compared with the acoustic test data. The SEA response is in a good agreement with the test data after approximately 300 Hz.

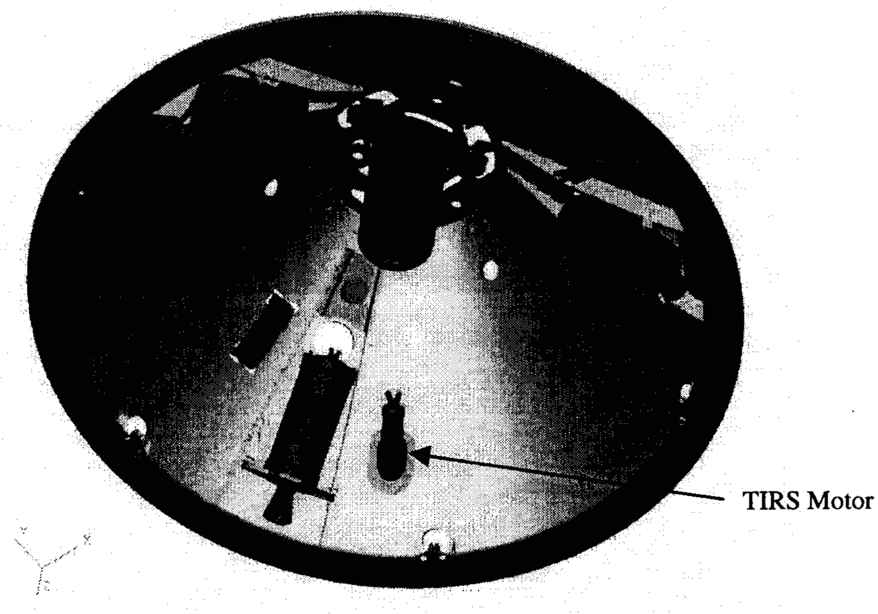

Figure 5-3: TIRS Motor on the Backshell (2.74 Kg).

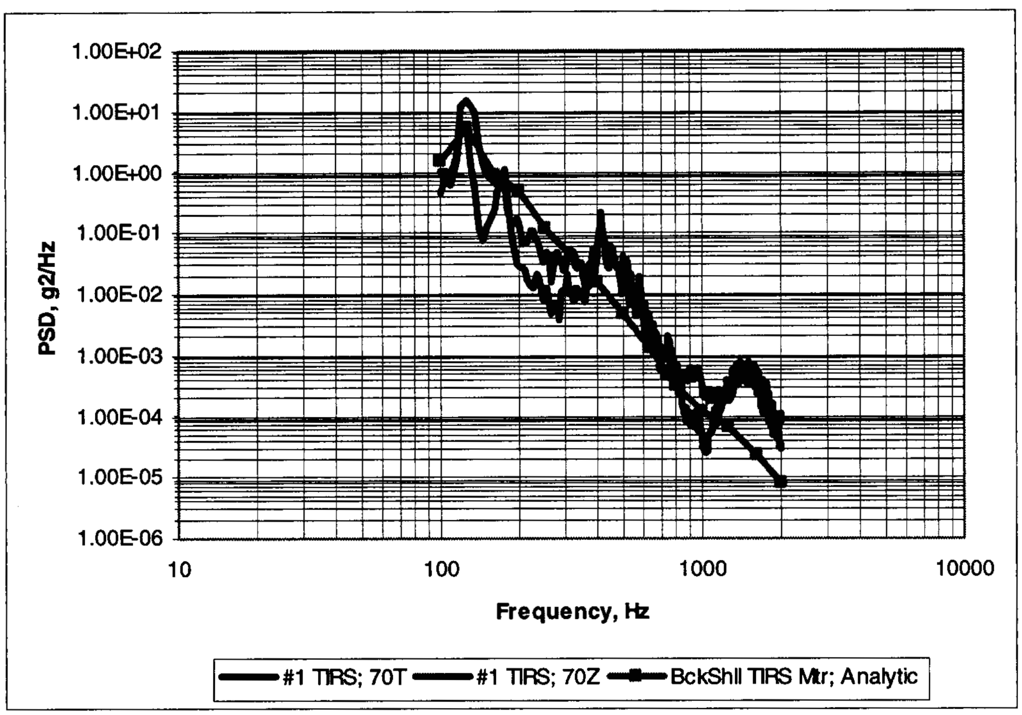

Figure 5-4: Analytical Response of the TIRS Motor with the SEA Panel Vibration Input – The analytical response of the TIRS motor is in a good agreement with the acoustic test data.