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Modal Survey of the Space Shuttle Solid Rocket Motor Using Multiple Input Methods

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The ability to accurately characterize propellant in a finite element model is a concern of engineers tasked with studying the dynamic response of the Space Shuttle Solid Rocket Motor (SRM). The uncertainties arising from propellant characterization through specimen testing led to the decision to perform a modal survey and model correlation of a single segment of the Shuttle SRM. Multiple input methods were used to excite and define case/propellant modes of both an inert segment and, later, a live propellant segment. These tests were successful at defining highly damped, flexible modes, several pairs of which occurred with frequency spacing of less than two percent.

INTRODUCTION

Morton Thiokol, under contract to the NASA Marshall Space Flight Center, has developed detailed finite element models for studying the behavior of the Space Shuttle SRM. These models are being used to assess both SRM response to a variety of load cases including stacking, static firing, and liftoff as well as the impact of SRM design changes. An important parameter in these highly refined models is the material properties of the solid propellant grain. The propellant is a viscoelastic material whose properties vary with temperature, frequency, and strain rate. Since the solid propellant has a noticeable influence on the structural characteristics and behavior of the SRM, the accurate determination of its properties is very important to the modeling and analysis effort.

Traditionally, propellant dynamic modulus was characterized through rheometric dynamic spectrometer (RDS) specimen testing. The major benefits of RDS testing are associated with the specimen's compact geometry and ease of data acquisition. The major drawbacks occur in relating the specific propellant stress-strain state being modeled to the specimen pre-strain and dynamic strain state during RDS testing.

Based upon the uncertainties of specimen testing and the importance of having an experimentally validated model, Morton Thiokol investigated the use of modal testing as a means to accurately determine propellant properties and improve

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confidence in the results from the specimen testing. Modal tests of SRMs performed a few years earlier demonstrated difficulty in exciting propellant modes and in correlating the analytic model with the experimental results. It was felt, however, that the advances in modal testing and system identification techniques that had taken place since the earlier tests could overcome the limitations encountered before. In particular, multiple input random excitation [1] and improved parameter estimation techniques [2,3] had been shown to be capable of handling the difficulties associated with symmetric, complex structures [4,5]. Recent improvements in system identification and model correlation methods [6,7] gave confidence that the SRM analytic model could be adjusted to match the results from a modal test. The decision was made to perform a modal survey on both an inert and a live propellant SRM segment.

The choice of testing a single segment rather than multiple segments or an entire motor was based upon maximizing the chances to obtain useful data for determining propellant behavior, while minimizing the unwanted and unneeded effects of joints and other SRM components. Modal testing of a complete SRM, which defined case and joint characteristics, had been performed previously on an empty case after static firing. Additionally, a test of a complete SRM would require significantly more time to plan and prepare, which would delay the date when a correlated model would be available.

The important elements that comprised the SRM modal survey were (1) choice of test article, (2) boundary conditions, (3) location and type of exciters, (4) instrumentation locations, and (5) excitation and data analysis methods. These five elements are discussed in this paper, along with the significant results and conclusions that arose during the modal survey.

TEST SETUP

In order to improve the likelihood of exciting propellant modes, an exciter location directly on the solid propellant was desired. Safety considerations dictated that an inert segment be used if propellant excitation was planned. A simulated free-free boundary condition was chosen with the segment oriented horizontally and supported underneath with an air bag system. The goal of the support system was to have the highest rigid body mode at least 2.5 times lower than the lowest flexible mode.

A single Shuttle SRM segment with propellant weighs approximately 297,000 pounds. The pretest finite element model was used to study various test requirements. A set of exciter locations that would define the modes felt to be most important for post-test model correlation was determined using the model. The analysis also indicated that excitation levels in the 200 to 2,000 pound (RMS) range were required in order to produce response levels that could be measured with high sensitivity accelerometers. To meet this requirement, as well as frequency content and exciter displacement requirements, electrohydraulic exciters were chosen. The model was also used to determine the optimum transducer locations which would ensure measurement of the important modes. A new finite element model reduction method [8] that employs the analytic mode shapes was used to define a mass matrix corresponding to the transducer locations. The mass matrix was used to calculate orthogonality and cross-orthogonality. This analysis resulted in 230 accelerometers distributed at 136 locations--64 on the segment case, 16 on the propellant faces, and 56 inside the segment along the bore.

Sixteen of these were actually imbedded in holes drilled into the inert propellant.

TEST PERFORMANCE

The SRM segment was instrumented with a fixed set of accelerometers to avoid the problems associated with relocating transducers during the test. The hydraulic exciters equipped with load cells were attached to rigid supports and large masses to eliminate their interaction with the segment. A photo of the test setup is shown in Figure 1.

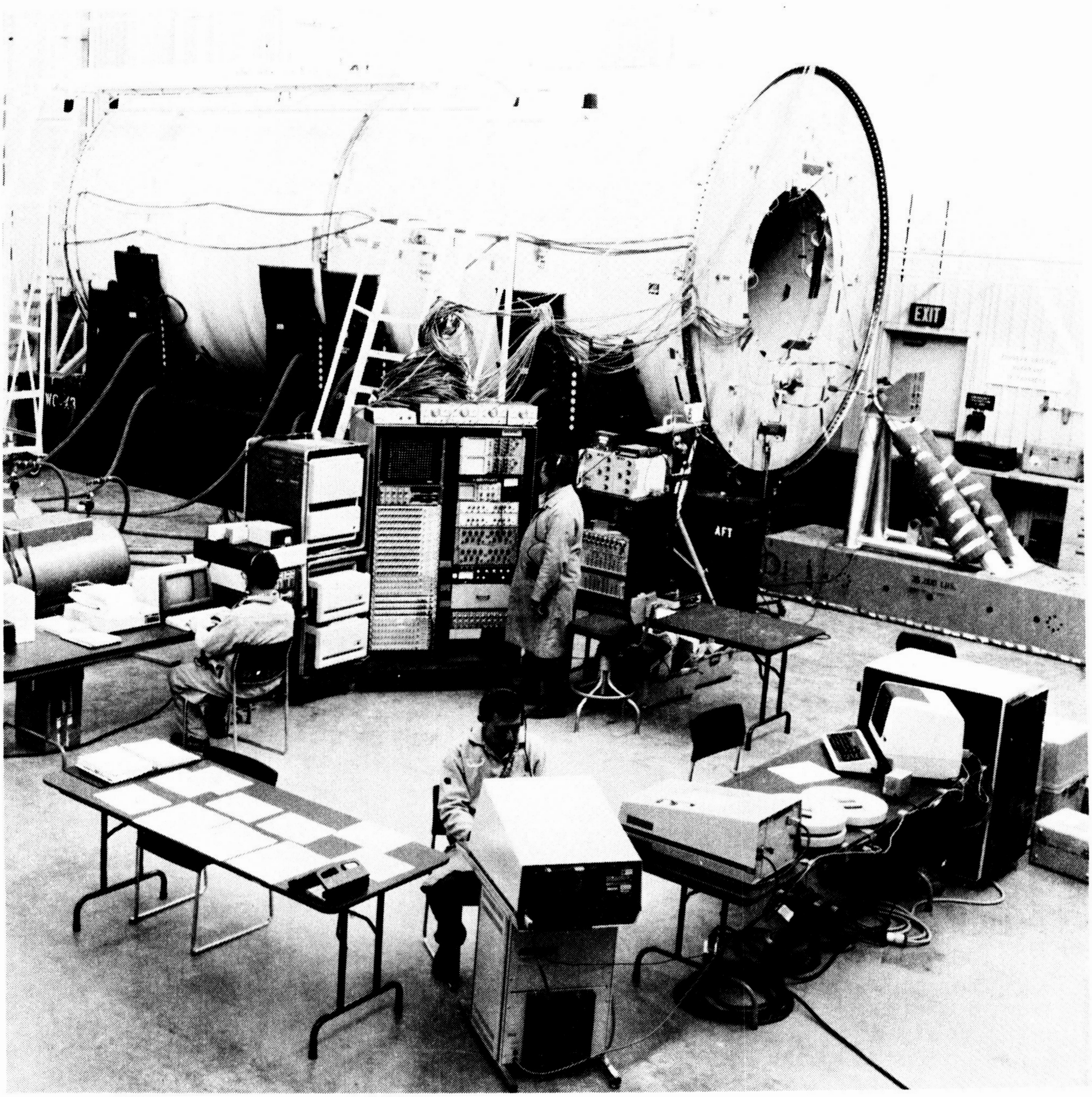


Figure 1. Test setup for modal survey of inert SRM center segment.

The data collection system, as diagrammed in Figure 2, included the capability for performing multiple input random excitation testing using 16 simultaneous channels and multiple input sine excitation using 244 simultaneous channels. The sine excitation part of this system has a number of advanced features, such as closed-loop exciter control, which have improved this traditional aerospace method [9].

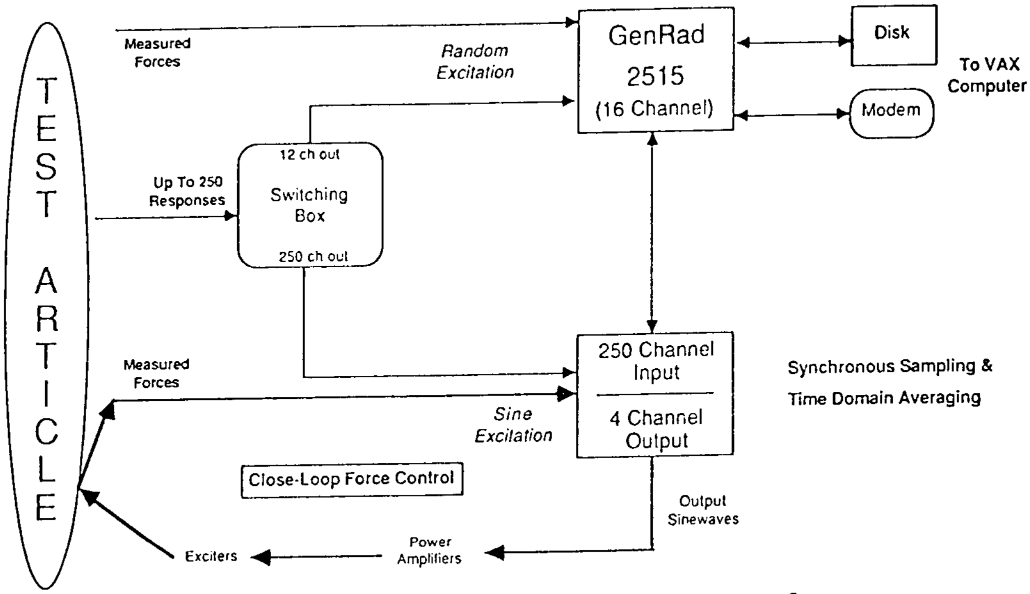


Figure 2. Data collection system for
multiple input random and multiple input sine excitation.

Initial random excitation of the SRM was performed to determine which combination of exciter locations would define the modes. Four exciter locations, depicted in Figure 3, were investigated. Three of these were on the SRM case; one was attached directly to the inert propellant. The initial frequency range for the test, based upon the pre-test model, was planned for 0 Hz to 16 Hz. It was discovered immediately that the flexible modes of the segment were much higher than expected, and the frequency range was increased to 64 Hz. This initial testing also indicated that the axial propellant location was not a good place for an exciter because of local flexibility. A large portion of the excitation energy was absorbed locally, which resulted in poor excitation of global modes. This can be seen in the frequency response function, plotted in Figure 4, where the response in the 5 Hz to 60 Hz range is dominated by the flexibility of a mode near or above 60 Hz.

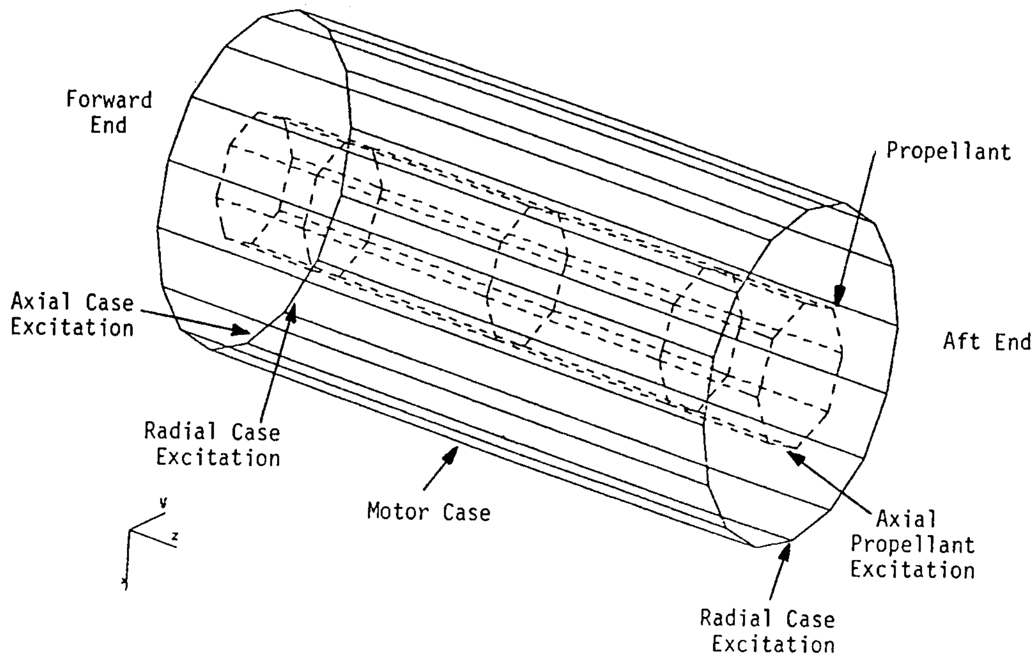


Figure 3. Exciter locations and subset of measurement locations.

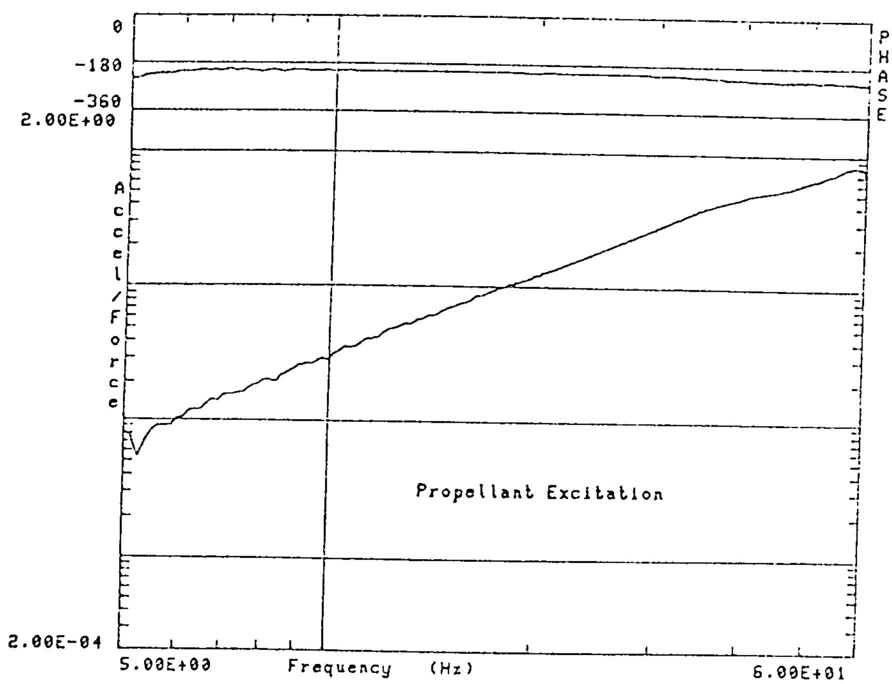


Figure 4. Driving point frequency response function for propellant excitation shows a large amount of local flexibility.

The three SRM case exciter locations, one axial and two radial, were chosen for a multiple input broadband survey. This multiple input random test was performed to assess quickly the modal frequencies, shapes, and damping of the SRM. The survey produced 690 frequency response functions (frf) and was completed in less than four hours. A typical frf from the survey is shown in Figure 5. It shows the characteristics of both the rigid body modes, below 10 Hz, and the more highly damped flexible modes above 10 Hz. The multivariate mode indicator function [10] was used to determine more precisely the number and frequency of the modes in both ranges. See Figure 6.

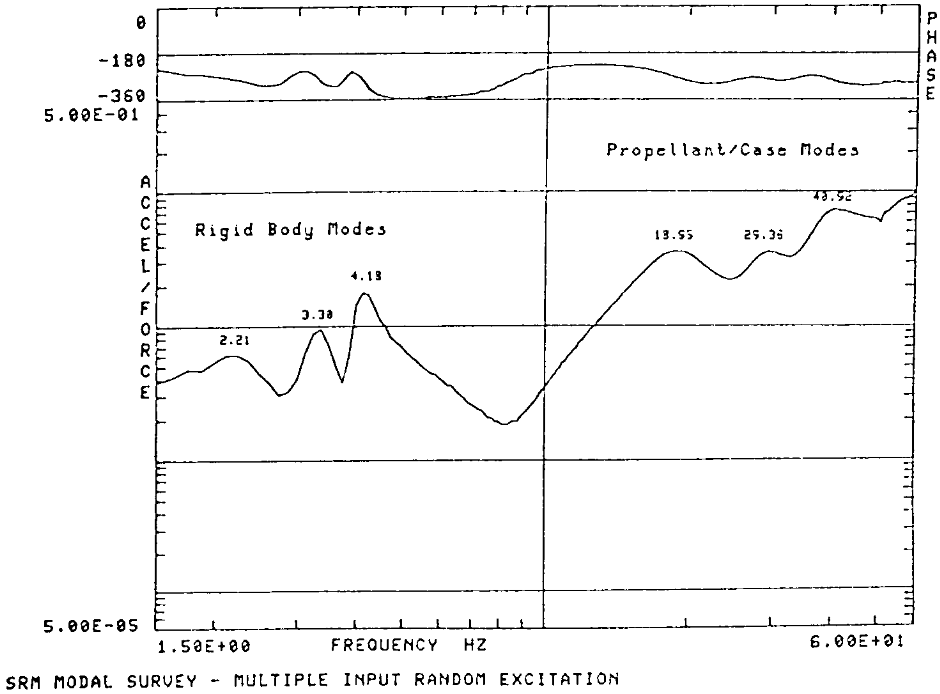


Figure 5. Typical frequency response function from the three exciter random survey on the inert segment.

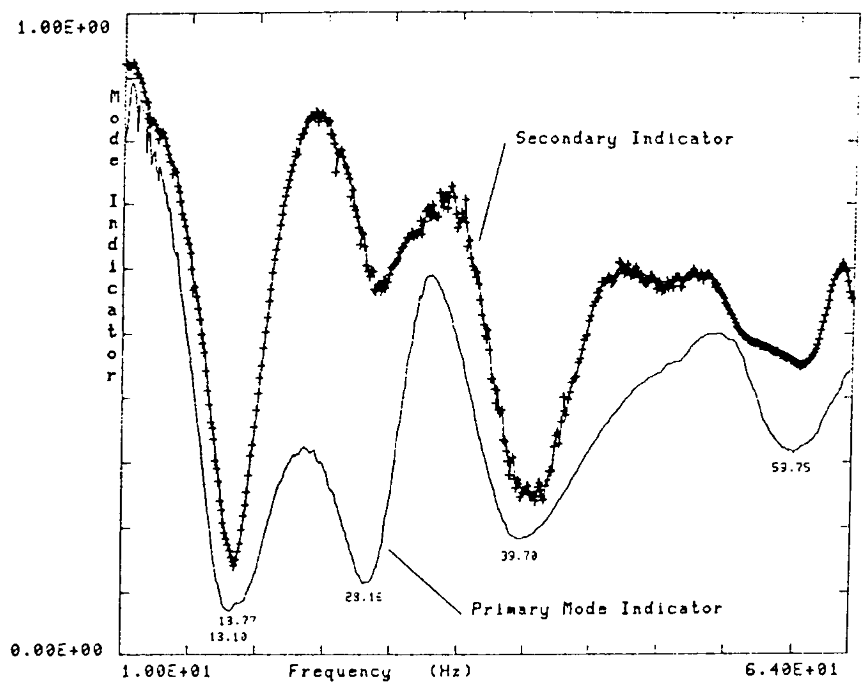
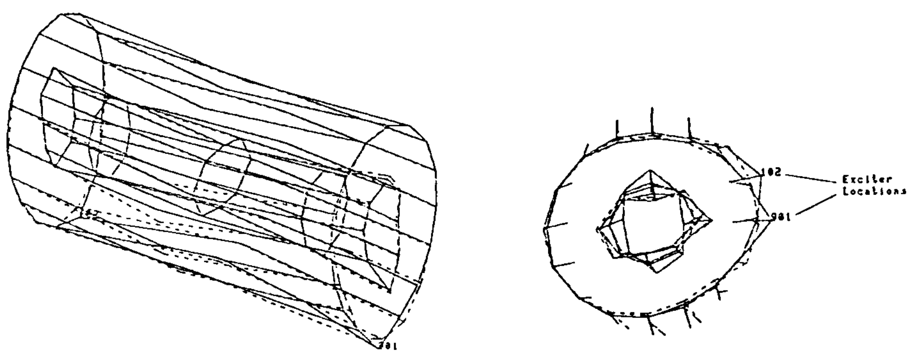


Figure 6. Multiple input frf are used to compute indicator functions which show approximately six modes between 10 Hz and 64 Hz.

The frf were analyzed first using a fairly straightforward "weighted total response" technique [11] to see if the modes made sense and to spot any malfunctioning or erroneously scaled transducers. Inspection of the mode shapes showed that, while this method identified the basic mode shape, it did not work well for transducers in the vicinity of the exciter locations. At these locations, there was enough local flexibility to give large errors in the mode shape coefficients computed using the total response method. This can be seen in the comparison of mode shapes depicted in Figure 7. The solid lines plot the mode shape for the 29 Hz saddle mode, computed using the weighted total response method. The dashed lines plot the same mode computed using the "direct estimate" method, described later in this paper. Two of the exciter locations are identified. The end view plot of the shapes clearly shows that these are the locations where the differences exist. The total response method uses the value of the frf at the resonant frequency as the mode shape coefficient. At these exciter locations, this results in an overestimate of the modal coefficient because the contribution of the response from the higher frequency, locally flexible mode exceeds that of the 28 Hz mode.



Isometric View

End View

Figure 7. Shape comparison for 29 Hz mode computed using weighted total response (solid line) and direct estimate method (dashed line).

The frf were next analyzed using the polyreference parameter estimation technique [2]. The polyreference method had performed well on many lightly damped structures with high modal density, including structures with symmetry. Because the SRM data was considered high quality, it was expected that the polyreference method would produce good results. Unfortunately, it seemed to have a great deal of trouble with this data. In retrospect, several possibilities for the problems became clear. The polyreference method that was employed was a time domain version (frequency domain polyreference versions were not available at the time). This means the frf are transformed to the time domain before the modal extraction begins. Because of the highly damped nature of the modes, the time domain (impulse response) data rapidly decays to zero. A second reason for the problems was the effect of the local flexibilities of the structure. Local flexibilities are usually seen in the form of higher frequency modes outside the range of interest. The formulation of the polyreference method does not allow for an accurate treatment of these residual modes.

The next method applied to the frf was the frequency domain "direct estimate" method [3]. Besides operating in the frequency domain, it directly handles residual modes outside the analysis range. This method produced very consistent and sensible results. It overcame the difficulties associated with the total response method for mode shape calculation, described earlier. It also enabled the separation of closely spaced modes. Table 1 lists all of the modes identified in the inert modal survey. The Forward Oval and Aft Oval modes are separated by less than 0.2 Hz. The direct estimate method was able to clearly identify these two heavily damped, closely spaced modes, as shown in Figure 8.

Table 1. Modes identified in the center segment inert propellant test.

Mode Number	Frequency (Hz)	Damping (C/Cr)	Mode Description
1	2.137	0.148	Rigid body pitch about bottom
2	3.322	0.052	Rigid body bounce
3	4.142	0.035	Rigid body pitch about top
4	4.998	0.035	Rigid body roll about top
5	18.681	0.172	Forward Oval (n=2,m=1)
6	18.806	0.161	Aft Oval (n=2,m=1)
7	28.980	0.090	Saddle (n=2,m=2)
8	40.867	0.139	Forward Triangular (n=3,m=1)
9	41.524	0.118	Axial Propellant (driven on propellant)
10	42.489	0.097	First Bending
11	60.249	0.104	Local Propellant

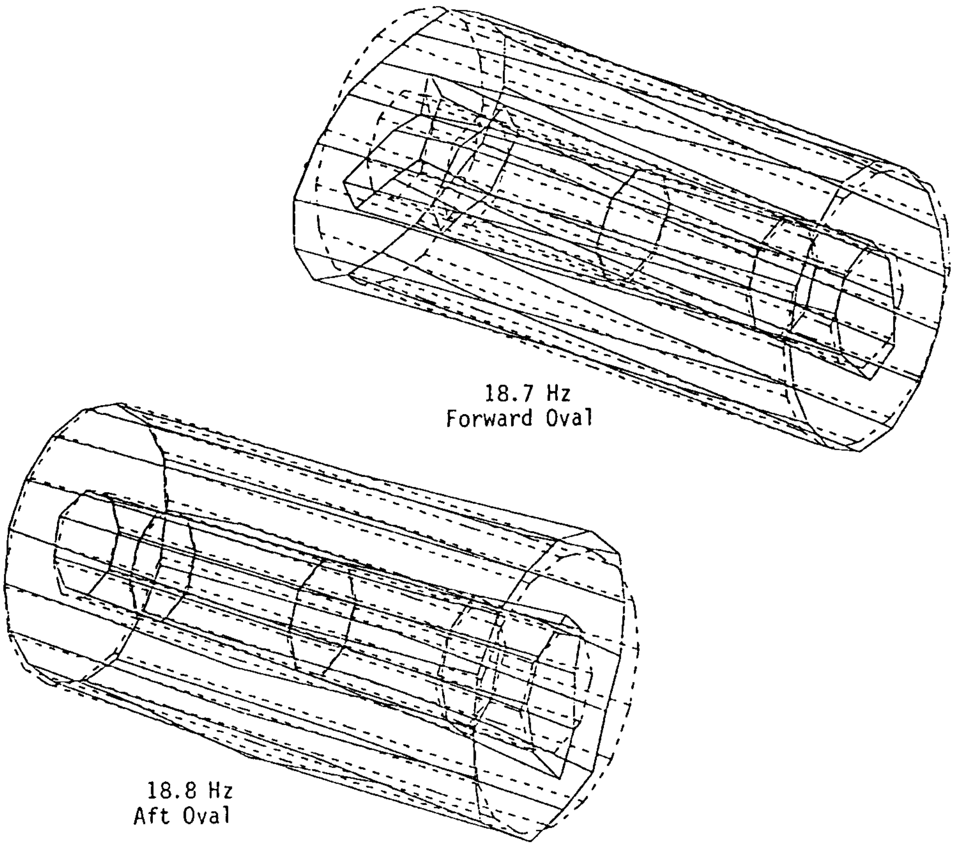


Figure 8. The direct estimate method was used to compute and separate these two closely spaced modes.

Because of the large differences between the predicted and measured mode frequencies, Morton Thiokol personnel felt that a modal test of a segment with live propellant was needed to ascertain the true properties of the solid propellant. Additionally, questions were raised about the effect of aging since the inert segment was several years old. A second test would add confidence in the propellant properties determined through the modal survey.

The inert survey had established that high quality results could be obtained using excitation on the segment case and that the test could be performed safely. A test of a live segment was planned and performed along the lines of the inert segment. The case exciter locations were the same, which eliminated the need for additional fixturing. The propellant exciter location was deleted for safety reasons. Measurement locations were very similar, with the deletion of the interior propellant measurements. The inert test indicated that these measurements did not give any additional relevant data.

The live propellant modal survey was performed several weeks after the inert test. A three-input random survey identified a set of modes which were very similar to the inert segment. The similarity in the two segments is evidenced by the frf comparison shown in Figure 9. The rigid body mode frequencies did not shift while the flexible modes of the live propellant segment appear 5% to 10% lower than those of the inert segment. This suggested that the live propellant has a lower modulus than the inert. The complete set of modes identified in this second modal survey is shown in Table 2.

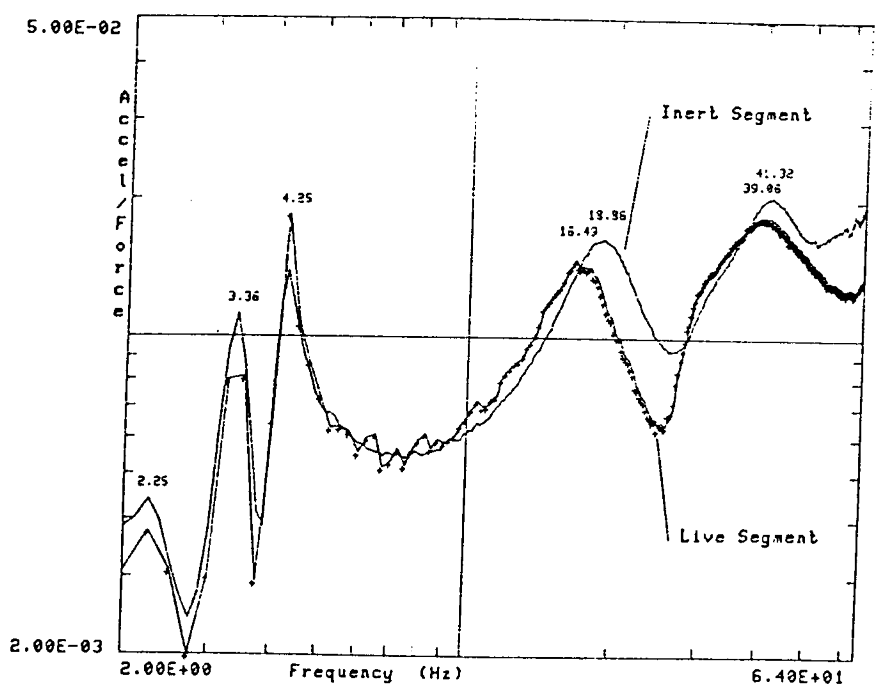


Figure 9. Comparison of frf for the inert and live propellant segment tests indicates the live propellant is more flexible.

Table 2. Modes identified in the center segment live propellant test.

Mode Number	Frequency (Hz)	Damping (C/Cr)	Mode Description
1	1.944	0.139	Rigid body pitch about bottom
2	3.198	0.068	Rigid body bounce
3	3.762	0.071	Rigid body pitch about top
4	4.752	0.036	Rigid body roll about top
5	14.647	0.210	Forward Oval (n=2,m=1)
6	16.726	0.174	Aft Oval (n=2,m=1)
7	28.163	0.097	Saddle (n=2,m=2)
8	29.131	0.177	Combined Forward Triangular and Saddle
9	38.634	0.209	Unclear mode
10	40.163	0.189	Aft Triangular and Case Bending
11	44.711	0.060	Case Bending mode
12	49.090	0.143	Propellant Axial
13	63.878	0.067	Propellant Axial
14	97.919	0.103	Local case mode

In both center segment modal surveys sinusoidal excitation was used to excite the segment to higher force levels to see if the modal frequencies, and possibly the propellant modulus, would change as a function of force. Additionally, mode shapes were computed using sine excitation for comparison to the results achieved using random excitation. Force patterns for tuning and exciting individual modes were computed from the random survey frf using the multivariate mode indicator approach [9,10]. This approach uses force patterns associated with each minimum of the indicator function. In the case of two closely spaced modes, the force pattern associated with the secondary indicator function was used. In general, the force patterns predicted by the indicator functions were quite good at isolating individual modes. Variations on these force patterns were also tried but were not found to offer any additional improvement.

The data from sinusoidal excitation of individual modes was acquired by holding the force pattern constant during a frequency sweep around the resonance. The force pattern was maintained via the closed loop control system, diagrammed in Figure 2. An incremental sine sweep was then performed, and frequency response functions were computed. The benefit of the short sweep as opposed to a single frequency dwell is that the direct estimate parameter estimation method could be used to further remove the effects of modes other than the one being tuned. Mode shape comparisons between the random and sine tests for the live segment are shown in Figures 10 and 11. These are two closely spaced modes with distinctly different shapes that occur near 29 Hz.

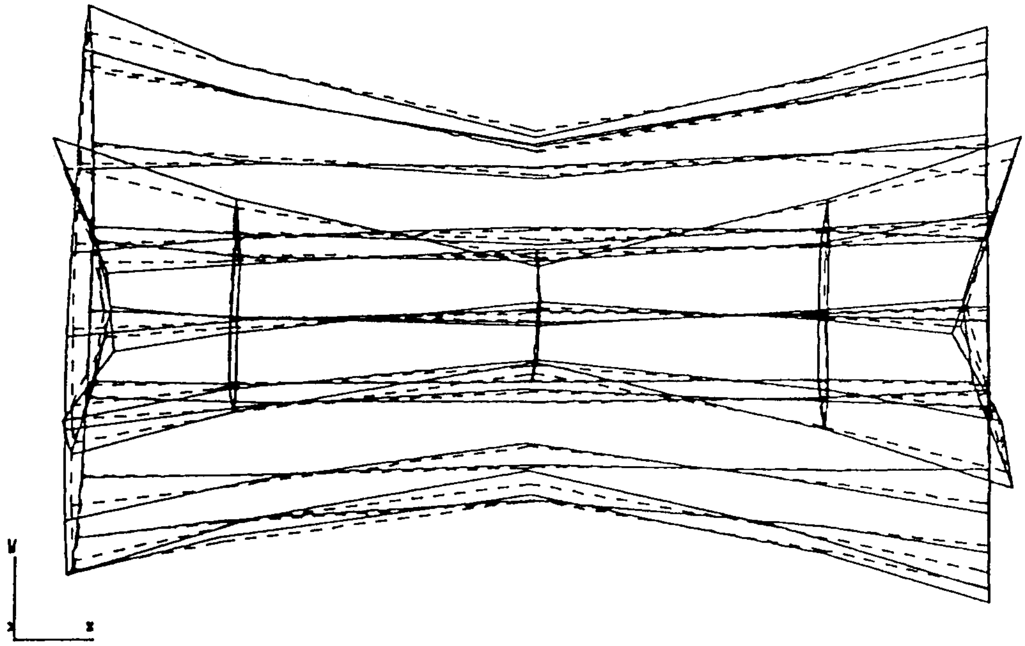


Figure 10. Comparison of 28.2 Hz saddle mode computed from sine and random excitation shows very good agreement.

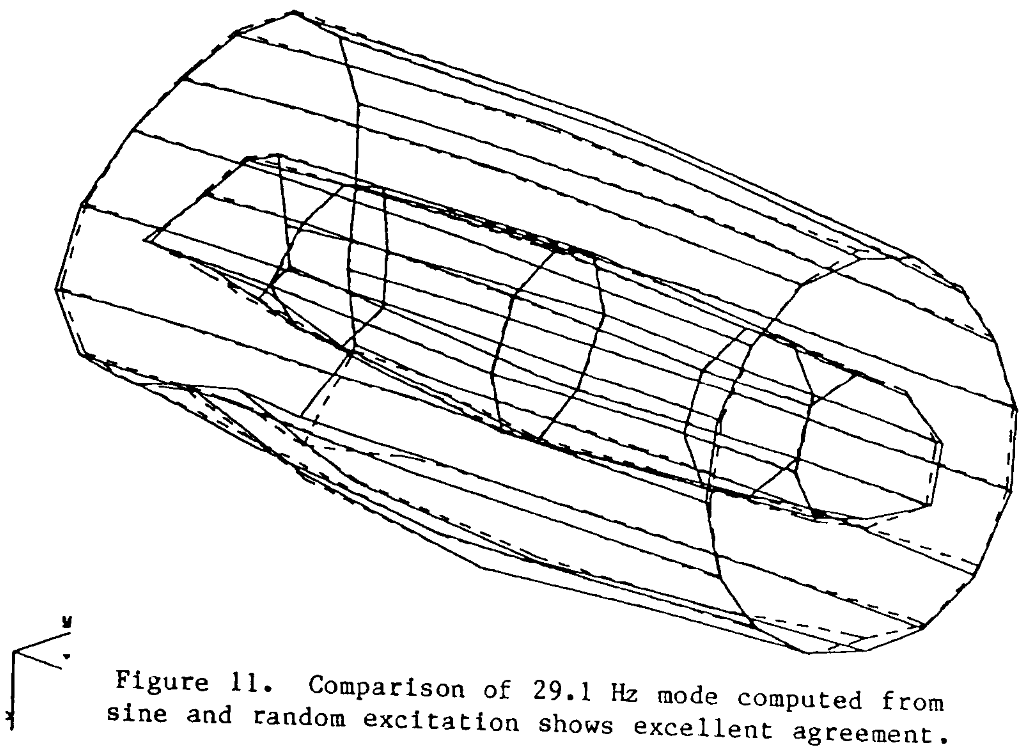


Figure 11. Comparison of 29.1 Hz mode computed from sine and random excitation shows excellent agreement.

After each mode was tuned and the frequency sweep completed, excitation was performed at several force levels to see if the mode frequency would change. Force levels from 50 pounds to 2000 pounds were used. Although frequency shifts had been expected due to the nature of solid propellant, only minor changes on the order of 2% or less were observed.

The modal data from these two modal surveys was used in a correlation and system identification process that resulted in an updating of the finite element model. This part of the project and model update results will be documented in an upcoming paper [12]. As a result of these tests Morton Thiokol was able to obtain better agreement between propellant properties determined from RDS specimen testing and those determined from the model updating process. Three-dimensional models of the entire SRM, including joints, nozzle, and skirts, are being built and analyzed using the propellant modeling methods and properties that were identified as a result of these modal surveys.

SUMMARY AND CONCLUSIONS

The results of modal surveys performed on two SRM center segments show that single segment SRM case/ propellant modes can be defined using multiple input excitation on the segment case. These modes have damping on the order of 10% to 20% (equivalent viscous damping), which is characteristic of solid propellant articles. Accurate estimation of mode shapes from frequency response functions requires the use of a frequency domain estimation algorithm capable of representing residual modes. Although many pure propellant modes (modes with no case deflection) were predicted by the finite element model, very few were identified, even though a propellant excitation location was used. We conclude that these modes are extremely heavily damped and are not contributors to overall SRM behavior.

Close agreement in frequency and mode shape was found between sinusoidal and random excitation. Mode frequencies as a function of force level did not vary noticeably. Closed loop force control allowed a force pattern to be maintained during a sine sweep. Force patterns predicted using frf from the random survey via the multivariate mode indicator approach were successful in exciting individual modes using sine excitation and multiple exciters.

The results of this test were used to update finite element models, improve confidence in the results from RDS specimen testing, and improve the accuracy of full SRM models being used in the SRM redesign program.

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