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336 358**DETAILED MODAL TESTING OF A SOLID ROCKET MOTOR  
USING A PORTABLE TEST SYSTEM**Dr. Vladimir Glozman  
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**ABSTRACT**

Modern analytical techniques have expended the ability to evaluate solid rocket motors used in launch vehicles. As more detailed models of solid rocket motors were developed, testing methods were required to verify the models. Experimental modal analysis (more commonly known as modal testing) of space structures and launch vehicles has been a requirement for model validation for many years. However, previous testing of solid rocket motors has not typically involved dynamic modal testing of full scale motors for verification of solid propellant or system assembly properties. Innovative approaches to the testing of solid rocket motors were developed and modal testing of a full scale, two-segment Titan 34D Solid Rocket Motor (SRM) was performed to validate detailed computer modeling. Special modifications were made to convert an existing facility into a temporary modal test facility which would accommodate the test article. The assembly of conventional data acquisition equipment into a multiple channel count portable test system has made modal testing "in the field" feasible. Special purpose hydraulic exciters were configured to apply the dynamic driving forces required. All instrumentation and data collection equipment were installed at the test site for the duration of the test program and removed upon completion. Conversion of an existing test facility into a temporary modal test facility, and use of a multiple channel count portable test data acquisition system allowed all test objectives to be met and resulted in validation of the computer model in a minimum time.

**INTRODUCTION**

The Titan 34D design was reassessed following the 34D-9 launch failure in 1986. Two SRM make up the solid propellant portion of the Titan 34D launch vehicle. An individual motor comprises of 5 1/2 segments. Each segment is about 3.3 meters (130 inches) long, 3.05 meters (120 inches) in diameter, and weighs about  $3.6 \times 10^5$  N ( $8 \times 10^4$  pounds). A cutaway view of a segment is shown in Figure 1.

The recovery program involved development of detailed finite element analysis models of the motor segments and the full motor assembly<sup>1</sup>. These detailed models were then evaluated to assess the loads (both static and dynamic) which occur prior to and during launch. The effects of launch dynamics on the segment joints as well as the overall system were evaluated during this program. A finite element model representation of the SRM is shown in Figure 2.

Previous testing of SRM typically involved static evaluation of the loads and deflections which were used to correlate computer models. Beam representations of the SRM were used to evaluate dynamics for controls information. The latest recovery program also focussed attention on the participation of dynamics in the behavior of the SRM joints. In order to validate the model dynamic predictions, an extensive modal test was performed on a two-segment portion of SRM in a specially modified test facility. Testing was performed with segments containing live propellant so that the true propellant properties were included in the test. Two segments were used in the test so that the joint which is used to connect the segments was an integral part of the evaluation and verification of the model.

An existing facility, which permitted testing of live propellant articles, was modified to handle the large test article while accounting for the live propellant. This facility was used in order to keep the program cost under control while allowing the facility to be readied in as brief a time as possible.

Because the remote test facility did not include test hardware, a portable system was assembled to allow all parts of the system to be moved to the site, set up for the test and then removed at the completion of testing.

This paper describes the configuration of the test facility for this special testing program and details the portable test system which was used for conducting the test.

## **TEST FACILITY**

The test article size and weight required that a test facility be identified which would accommodate the two-segment SRM specimen. In addition, the test was to be conducted below ground level for safety reasons. The test facility which was selected would satisfy this requirement, but its isolated location required that portable test equipment be used to perform the modal test. While the identified test site would accommodate the SRM test article, the existing site needed to be converted into a temporary modal testing facility.

The modal survey test facility consisted of two primary buildings. The main test building, where the modal testing was performed, contained a 6.1 meter (20 feet) deep by 5.5 meters (18 feet by 18 feet) square concrete lined test pit to accommodate the test article. A temporary instrumentation building was fabricated adjacent to the main

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<sup>1</sup>"Dynamic analysis and testing for the Titan 34D Recovery Program". SDRC Final Report to CSD, October, 1987.

building to serve as a storage and temperature conditioning facility for the SRM segments prior to their installation in the main test facility. This temporary building was also used to install some of the instrumentation to be used in the modal test prior to the assembly of the test article. Movement of the SRM segments between the buildings was accomplished using a crane. Each of the SRM segments was lowered into the test pit through a roof opening in the main test building. Final assembly of the segments then occurred in the main test facility where the test article was installed in the vertical orientation.

Since the main building was an existing one, special modifications to the building and the test pit had to be made in order to perform the modal test. The modal testing was to be performed with the two segments assembled and then suspended to simulate a free-free boundary condition. This free-free boundary condition was simulated by supporting the test article from the forward segment joint with an airbag suspension system. The two segment test article was supported from above to place the joints in tension as it is in flight. Since this suspension system had a very low stiffness associated with it, the rigid body modes of the test article on the suspension system were very low in frequency (below 2 Hz) which gave the appearance of a free boundary condition.

The suspension system was built over the top of the test pit. The overhead support assembly consisted of a tubular ring attached to the floor by four vertical strut assemblies. Twenty airbag isolators were mounted on top of the tubular ring for suspension of the test article as shown in Figure 3. A load plate was installed on top of the airbags. Steel rods and cables were attached to this load plate on one end and the test article on the other. A handling ring, installed on the upper joint of the test article, was used to attach the steel cables which ran from the test article to the suspension system. The parameters used for the generation of a finite element model to analyze the overhead support are listed in Table 1. The general layout of the test facility is shown in Figure 4.

In addition to the suspension system, a support stand had to be installed in the bottom of the pit to allow the test article to be stacked and assembled prior to the suspension system being attached and activated. This base support was comprised of a main supporting ring with eight equally spaced legs around the circumference. The base support was analyzed using a finite element model, and its main parameters are also summarized in Table 1. Final instrumentation was installed on the test article after the two segments were joined while resting on this base support stand. Once all of the test article assembly and instrumentation were completed, the airbag suspension system was inflated, lifting the test article off of the support stand.

Work platforms were also installed in the test facility which allowed access to different levels of the test article for installation of instrumentation and the attachment of hydraulic exciters. The dimensions of the specimen and the pit allowed access to install instrumentation around the joint between the two segments.

## **TEST FACILITY STRUCTURAL EVALUATION AND VERIFICATION**

Proof load testing of the overhead support structure was performed to verify structural integrity of the main elements of the assembly. This included testing of the upper ring with steel cable sling assemblies as well as the main frame with the airbags under the designed loading conditions. The test setup for the proof loading was as shown in Figure 5. A specially designed bottom ring was secured to the bottom of the test pit and connected to the sling assemblies by twenty steel stranded cables. Separate turnbuckles on each cable were used to achieve equal cable tension prior to pressurization of the suspension system. Four pressure gauges were used to control the airsprings as the air pressure was increased to that required for the proof test ( $8.27 \times 10^5$  Pascal or 120 psi). Four LVDT's monitored airspring heights in the range from 0.05 to 0.15 meter (2 to 6 inches). The total maximum proof load was limited to  $3.9 \times 10^5$  N ( $2.0 \times 10^5$  pounds) which is 25% higher than the suspended weight of the assembled test article.

During the proof test, the air pressure in the air springs was gradually increased and recorded every  $3.45 \times 10^4$  Pascal (5 psi), together with the recording of airspring heights and the upper ring position. After the maximum load of  $9.07 \times 10^5$  N ( $2.04 \times 10^5$  pounds) had been achieved, the air pressure was removed and the overhead support assembly and its mounting was thoroughly inspected. Since no sign of failure or plastic deformation was observed, the fixture had passed the proof load test and was approved for subsequent operations. At this time the positioning and stacking of the two-segment test article was performed in preparation for the execution of the modal testing program.

## **PORTABLE TEST SYSTEM**

A portable large channel modal test system allowed the remote testing to be setup and performed in six days. The excitation systems and the data collection equipment used were both designed and assembled to be easily transported and installed at remote facilities. The next sections describe the equipment which was used.

### **Excitation Equipment**

The size and heavy damping properties of solid rocket propellant dictated that large excitation forces be used for conducting the modal survey. Hydraulics exciters were chosen since the system size could be kept to a minimum which would allow it to be much more portable than electrodynamic exciters with equivalent force capability. The hydraulic exciters were powered using portable hydraulic pumps and actuated with high speed servo valve actuators. The high speed actuators allowed the frequency range of interest (2 to 128 Hz) to be met for the modal survey. Four hydraulic exciters were employed for the test. Two of the exciters were installed at the aft joint of the aft SRM segment. The other two exciters were installed at the handling ring of the forward segment. The exciter locations are shown in Figure 6.

Exciter locations were selected by using the finite element analysis model prior to the test. Predictions of the test article frequency response functions (FRF) were made and these were evaluated to determine whether all of the dynamic modes in the frequency

range of interest could be extracted with the exciters positioned at these locations. This type of evaluation allowed the fixturing which was required to attach the exciters to the test article to be fabricated ahead of time while giving high confidence for a successful test. The two shakers at the aft end of the test article were rigidly constrained to a backup structure. The shakers installed at the forward end of the test article were attached to reaction masses since there was no rigid structure which could be used to react against.

The hydraulic shakers are shown in Figure 7. Special consideration was given to the safety of using a hydraulic shaker attached to a solid propellant test article. Fittings were designed for attachment of the shakers to the test article which would serve as a mechanical fuse and limit the amount of force which could be applied to the SRM segments. With these fittings, if a preset force level limit was exceeded, the fitting would slip, thereby keeping any additional force from transmitting to the test article.

Both random and sinusoidal excitation signals were used to drive the test structure. The random signals were provided by independent sources so that burst random (or random transient) excitation [1] could be employed. Multi-Point Random (MPR) excitation [2] was used as the primary investigative excitation type for the modal survey. Confirmation of mode shapes and investigation of damping characteristics were performed using sinusoidal excitation with a closed loop Multi-Phased Stepped Sine (MPSS) [3] shaker control and mode measurement system.

### **Signal Measurement and Conditioning Equipment**

A high channel count data acquisition system was required for the test program to obtain all of the necessary FRF for the modal survey. Due to the nature of modal tests and the requirements for the stationarity of the data [4], roving instrumentation was not used. As a result, all of the instrumentation was installed prior to the test so that all data could be collected quickly once the testing was underway. A total of 230 accelerometers were installed on the two SRM segments, on the propellant bore, on the propellant inhibitor, and on the outer casing. These transducers were installed at 132 locations which had been defined by pretest analysis efforts. Figure 8 shows the distribution of the measurement locations which were used in the test. An equal number of amplifier channels were provided so that there was a one-to-one correspondence between the accelerometers and the signal conditioning. Load cells were installed at each of the shaker excitation locations to measure the applied force. The resulting force and accelerometer measurements were used to compute the FRF for the test article.

All of the signal conditioning equipment was installed in a standard 19-inch instrumentation rack which was used to transport the equipment to the test site. The same rack contained a switch box to select the set of data which was acquired at any time during the test. Oscilloscopes, which were used to monitor the signals from all channels during the data acquisition process, were also rack mounted for portability.

Having all of the test equipment installed in racks prior to shipment to the test allowed the setup time to be kept to a minimum while the test hardware was tied up. All of the

accelerometers, as well as the other control equipment and the data acquisition system, were installed over a four day period.

### **Data Acquisition Equipment**

The data acquisition system for this modal survey was built around a GenRad 2515 computer aided test system. This system is a 16 channel data collection and processing system. Using the four excitation signals from the load cells and twelve response measurements at a time, all of the measurements on the test article were made. The excitation signals were monitored continuously while groups of twelve responses were measured and the corresponding FRF were obtained. Multiple time ensembles were collected and averaged to compute the FRF. As each set of FRF was computed, the data was stored on the data collection system disk and transferred to the data analysis computer for processing. In order to collect all of the FRF data using random excitation, twenty data sets of twelve each were collected.

Sinusoidal data acquisition was performed in addition to the random excitation. The test data acquisition system has been modified with the addition of a 240 channel multiplexed data collection system for MPSS operation [5]. Using this hardware single frequency sine dwell mode shapes were measured and stored on the data acquisition system storage media. Multiple force levels were also used to determine the linearity of the dynamic response of the system. The mode shapes were transferred to the data analysis system where they were compared to the data obtained from the random survey; orthogonality checks were completed with respect to the analysis mass matrix.

### **Data Analysis Equipment**

A Vax computer was used to process the modal data at the test site. By having the data analysis computer available, the test data was immediately transferred to the analysis system for review. Data processing was performed while further data acquisition proceeded. This arrangement of the test system permitted rapid evaluation of the modal results to determine whether further testing was needed and allowed quick identification of any instrumentation errors which could be fixed prior to further data collection.

Data transfer between the data collection system and the data analysis system was performed using direct transfer of the storage disk as well as a communications link between the two systems. All of the modal parameters were extracted on the data analysis system. Then the mode shape results were transferred back to the data acquisition system where animation of the mode shapes were performed.

Figure 9 shows the entire setup which was used during the modal test program.

### **CONCLUSION**

Requirements for specialized tests often demand that remote facilities be used for testing. Even when test locations are convenient, extensive effort may be required to install all of the test equipment prior to the start of a test. Portable test equipment allows a test to be setup rapidly to reduce the impact on the overall program schedule. New sophisticated numerical algorithms have been developed and greatly improved the

collection of data during modal tests. The assembly of a complete portable modal testing capability has allowed modal testing to be performed in virtually any location with reduced setup time. This has kept overall test time and program costs to a minimum. Further improvements in the test hardware computational capability and portability have taken place since this test was conducted. Extremely sophisticated modal test laboratories can be quickly transported from one site to another keeping test time to a minimum.

## REFERENCES

1. Olsen, N.: "Excitation Functions for Structural Frequency Response Measurements". Proceedings of the 2nd International Modal Analysis Conference, 1982, pp. 894-902.
2. Hunt, D.L.; Peterson, E.L.: "Multishaker Broadband Excitation for Experimental Modal Analysis". SAE Paper 831325, 1984.
3. Vold, H.; Williams, R.: "Multiphase-Step-Sine Method for Experimental Modal Analysis". IJMA, 1986.
4. Chen, J. C.; Hunt, D. L.: "Application of Multiple Input Random and Polyreference Analysis Techniques to the Galileo Spacecraft Modal Test". 25th Structures, Structural Dynamics, and Materials Conference, AIAA-84-1069, 1984.
5. Hunt, D. L.: "A Modern Approach for Modal Testing Using Multiple Input Sine Excitation". AIAA Dynamics Specialists Conference, AIAA-87-0964-CP, 1987.

**Table 1. Support Structure Parameters.**

| <u>Structure</u>                | <u>Base Support</u>          | <u>Overhead Support</u> |
|---------------------------------|------------------------------|-------------------------|
| Dimensions                      | 3.1 m diameter by 1 m height | 6.7 x 6.7 x 2.5 m       |
| Material                        | A36 Steel Weldment           | A36 Steel Weldment      |
| Weight, kN                      | 6.7                          | 29.4                    |
| Design Load, kN                 | 800                          | 815                     |
| Maximum Vertical deflection, mm | 0.3                          | 1.7                     |
| Maximum calculated stress, MPa  | 74.4                         | 64.5                    |
| Factor of safety on yield       | 3.34                         | 3.85                    |

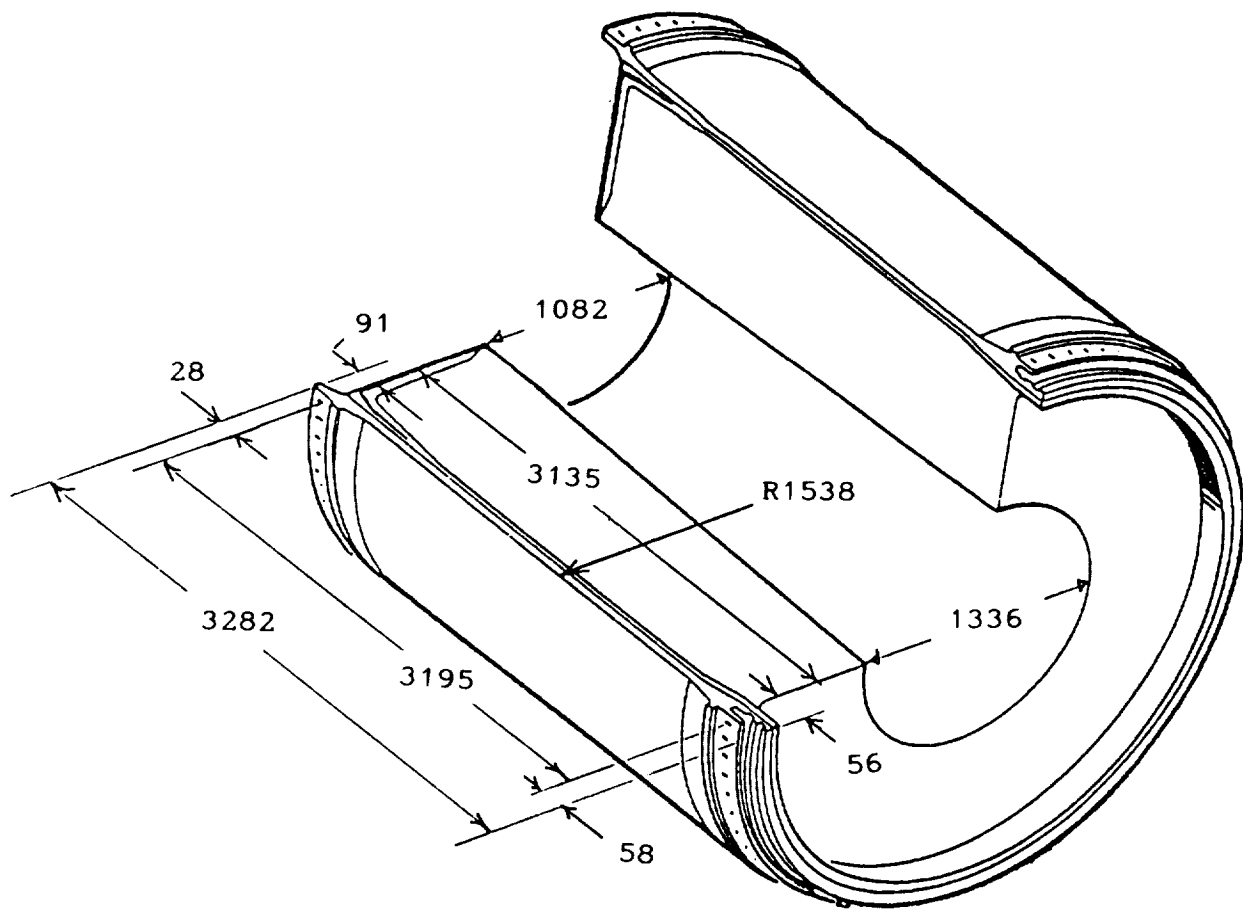


FIGURE 1. A cutaway view of the Titan 34D SRM segment showing the dimensions.



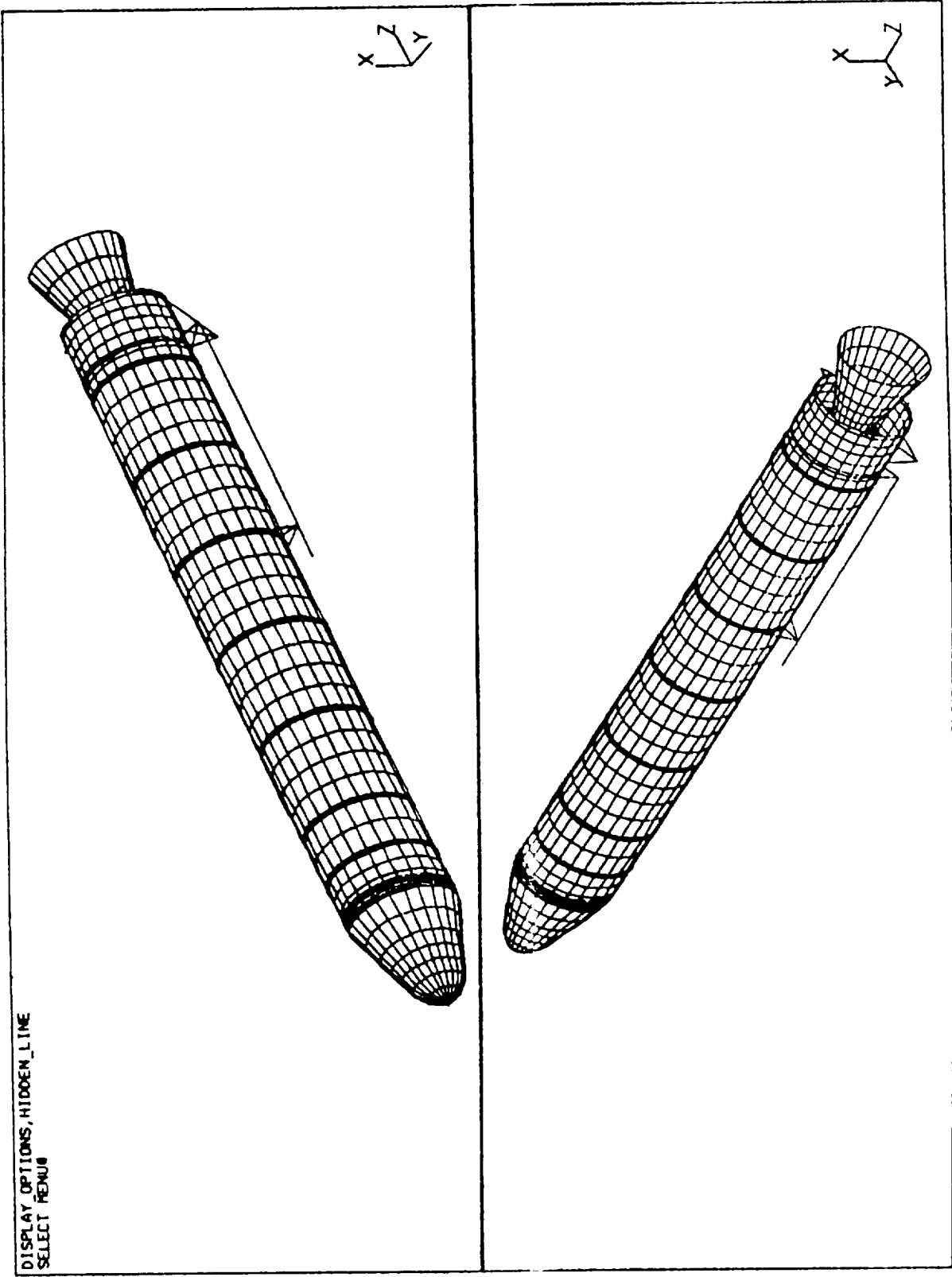


FIGURE 2. A finite element model of the Titan 34D SRM was developed in preparation for the modal test and for loads analysis.

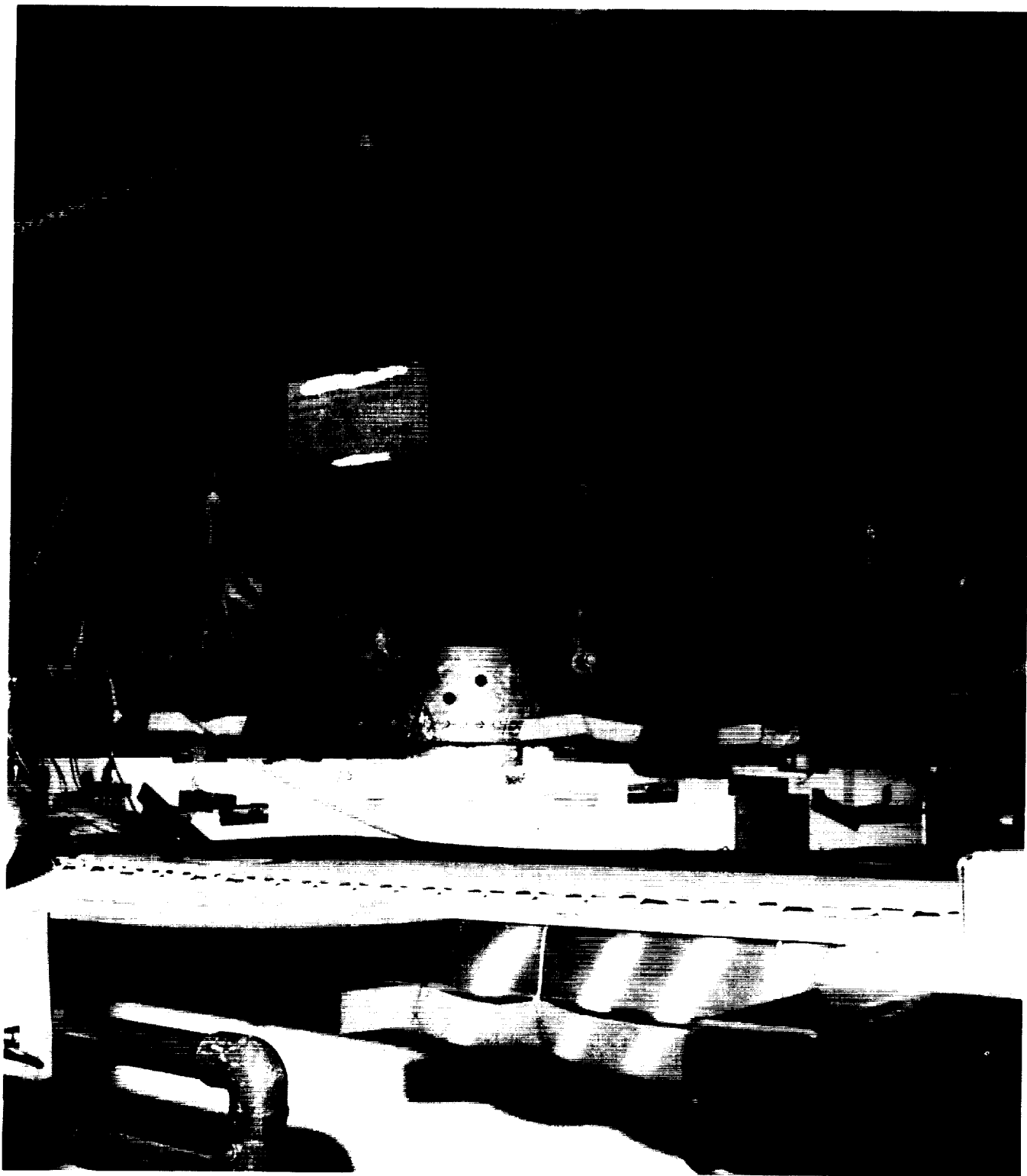


FIGURE 3. The test article suspension system used twenty airbag isolators to support the two segment assembly.

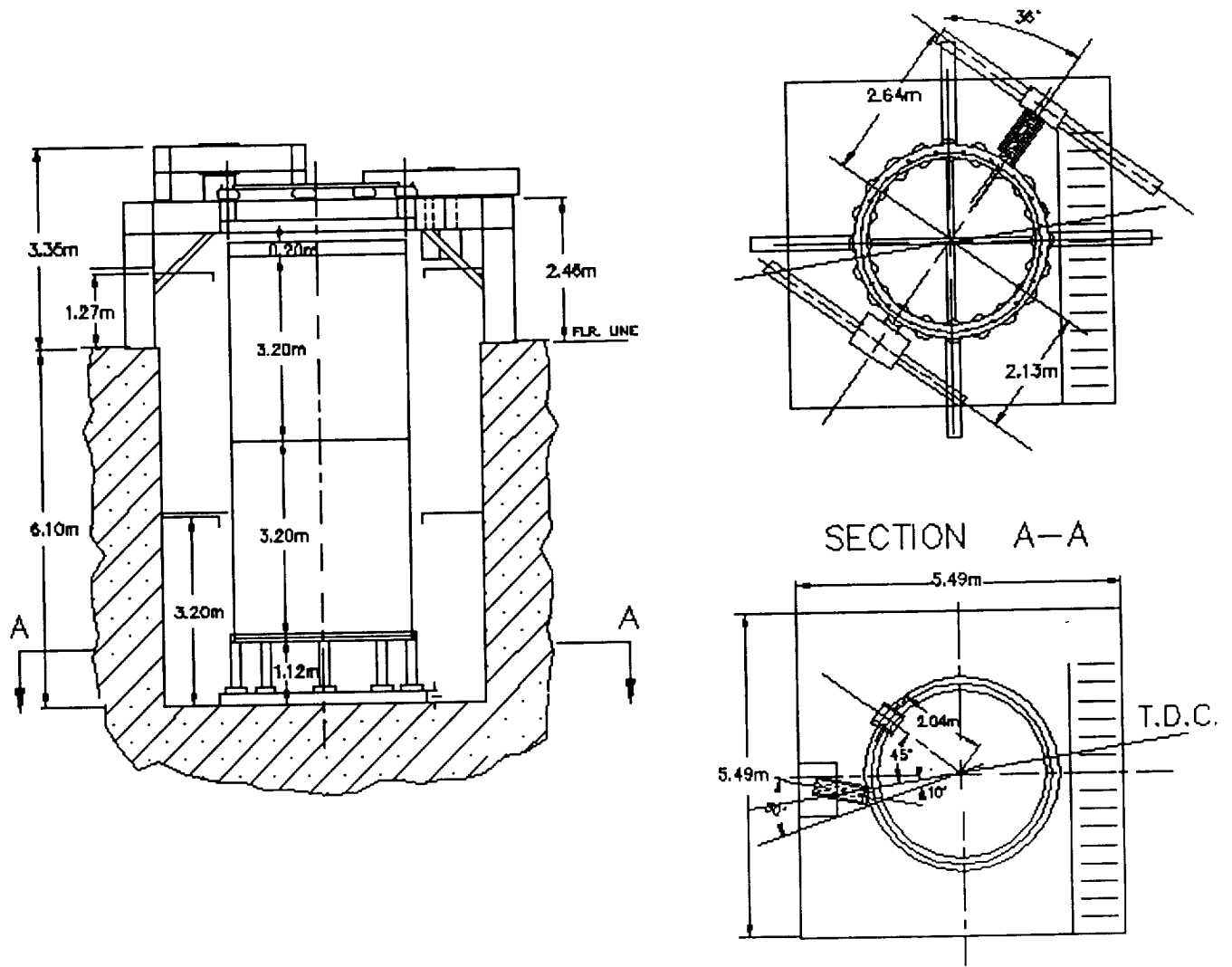


FIGURE 4. The test facility layout shows the orientation of the test article as installed.

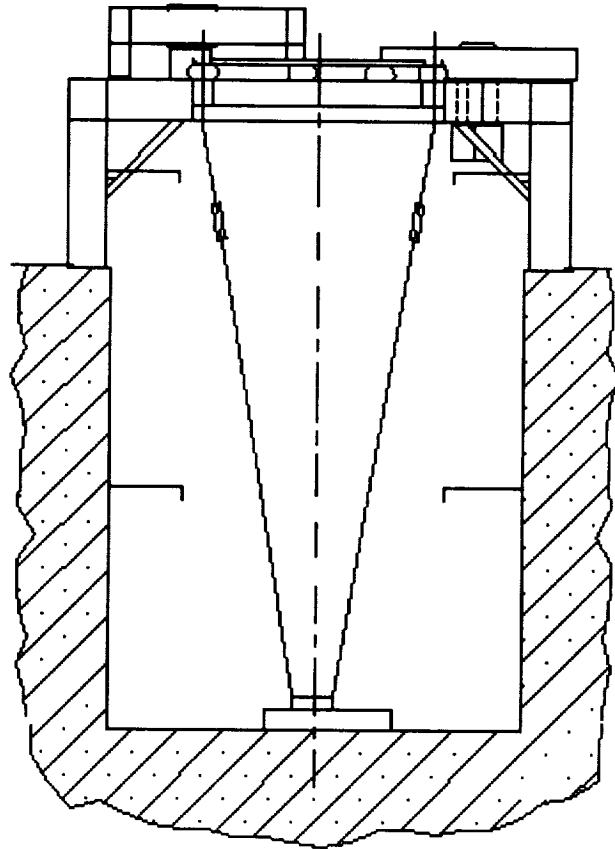


FIGURE 5. The configuration of the proof load test which was performed prior to installation of the test article to verify the suspension system.

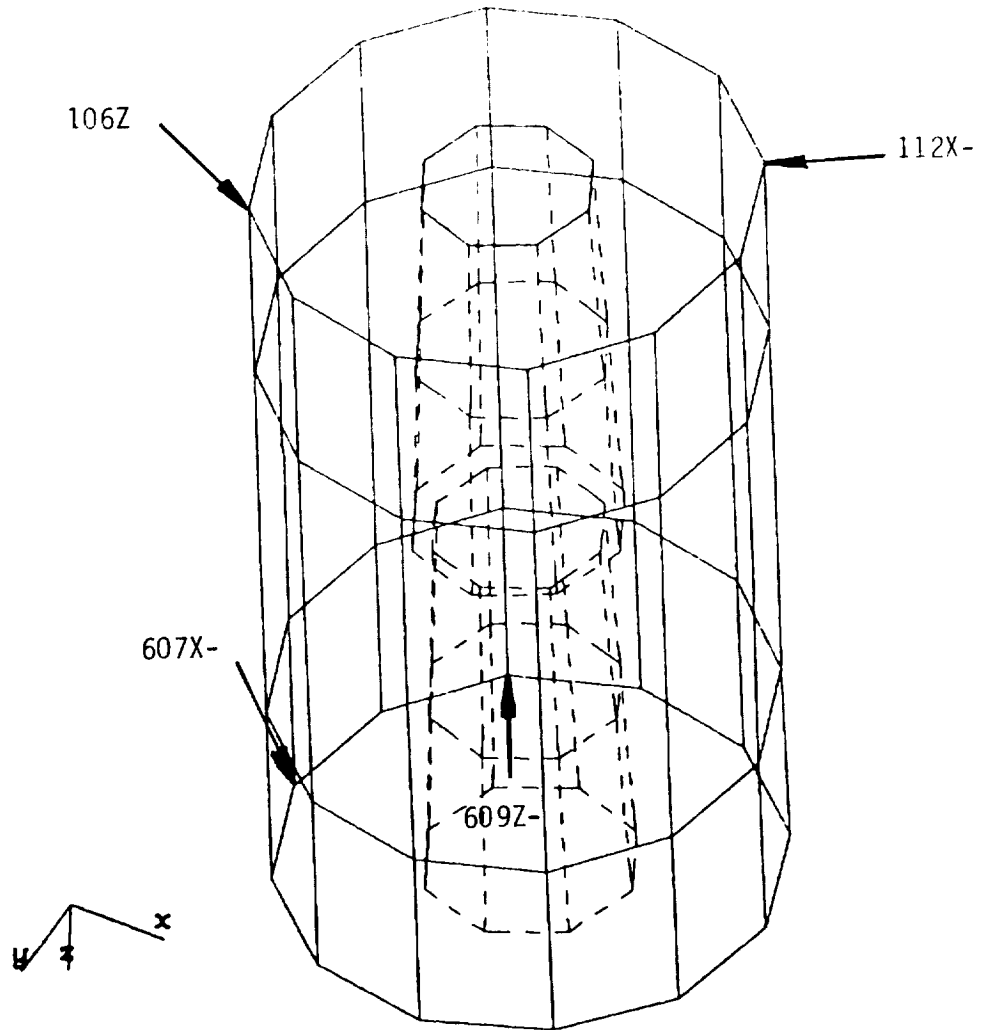
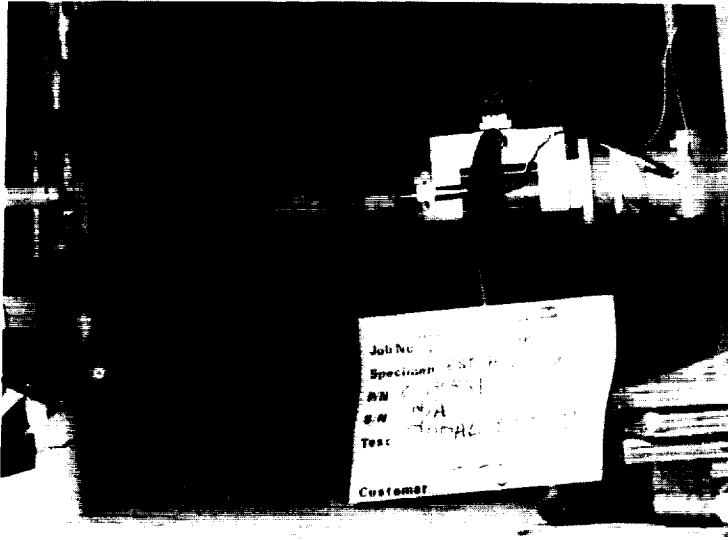
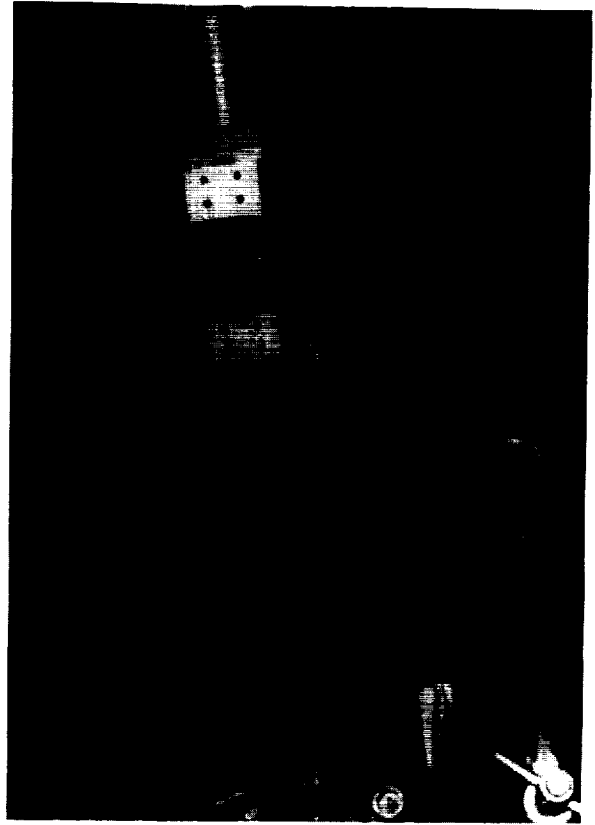


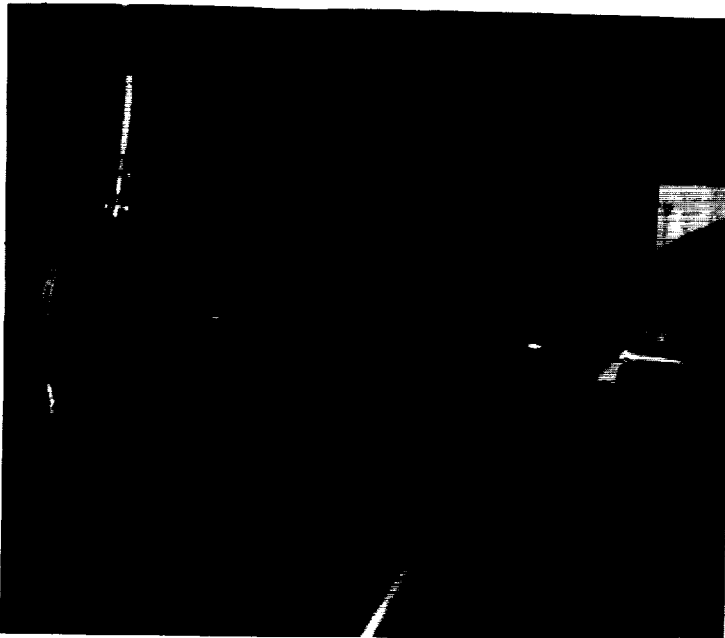
FIGURE 6. Four exciter locations were used to perform the modal survey: two at the top segment handling ring and two at the bottom segment flange.



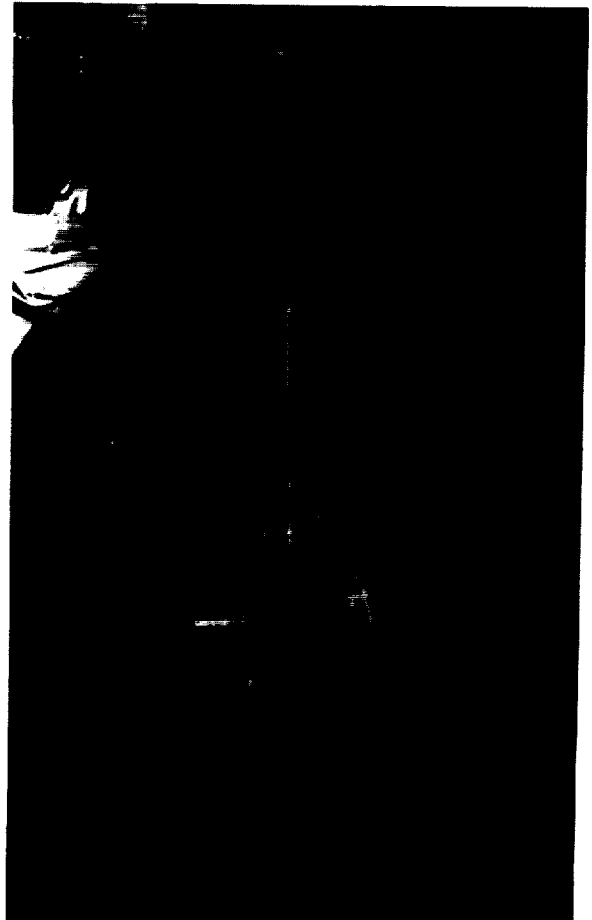
a)



b)



c)

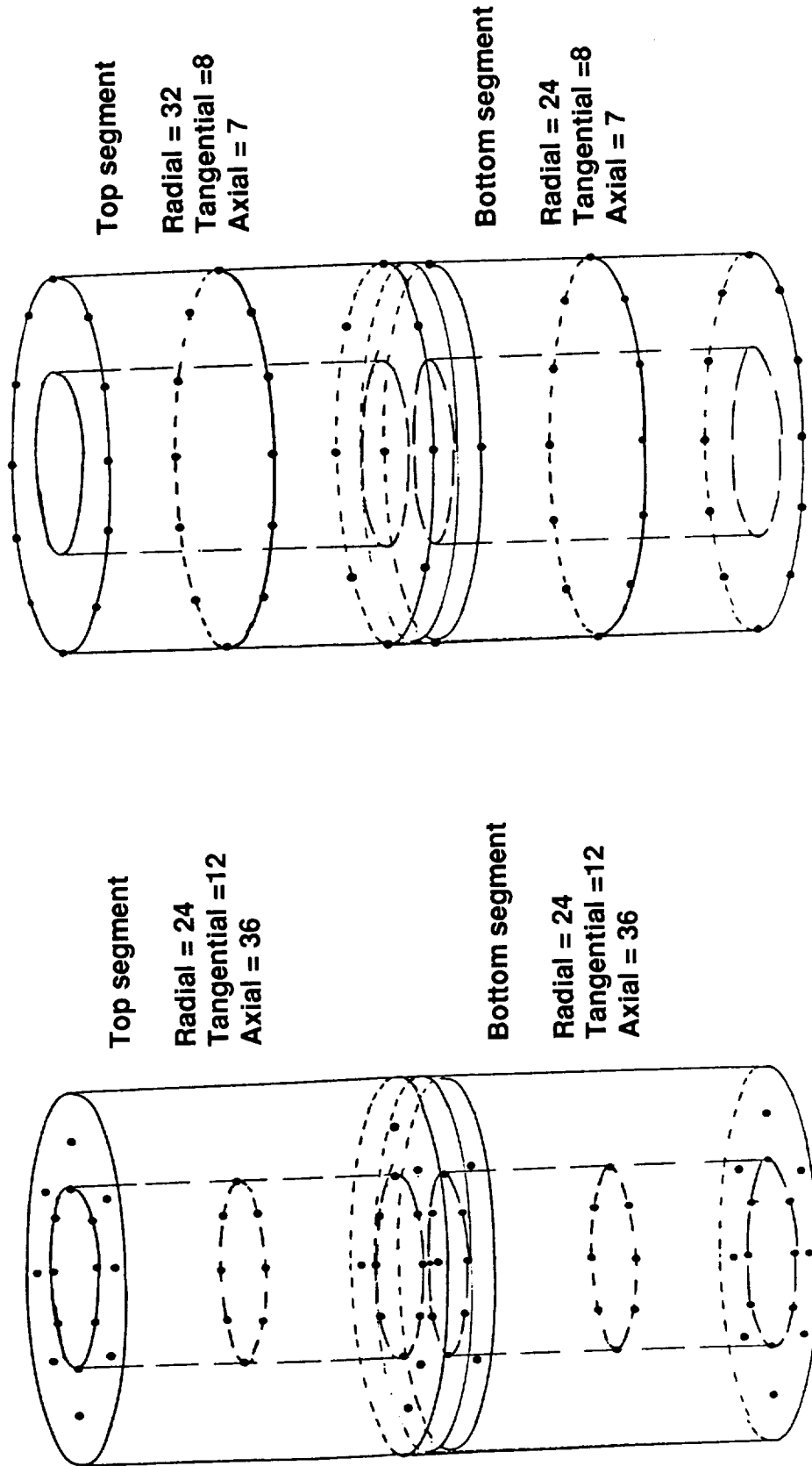


d)

FIGURE 7. The hydraulic exciters as installed:  
a) top segment radial exciter  
b) top segment skewed exciter  
c) bottom segment horizontal exciter  
d) bottom segment axial exciter

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**230 Accelerometers total were installed  
on the test article**



**144 accelerometers  
installed on exposed  
propellant**

**86 accelerometers installed  
on segment casing**

FIGURE 8. Accelerometers were installed on the propellant bore, propellant faces, and on the casing of both segments.

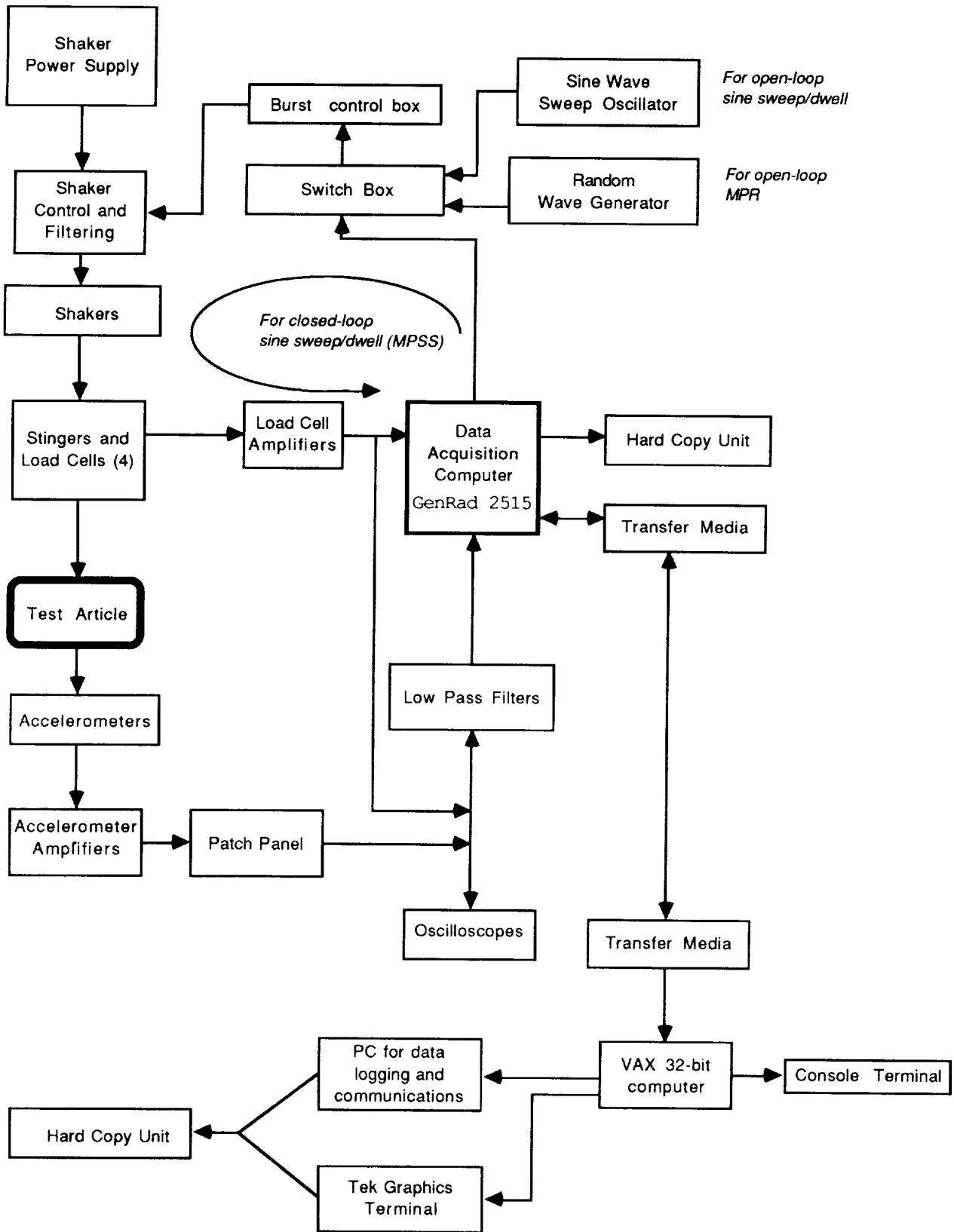


FIGURE 9. The computer controlled, multiple channel data acquisition system, and automated data analysis system allowed all data to be rapidly collected and analyzed.