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A METHOD OF EMBEDDING ACCELEROMETERS
IN SOLID PROPELLANT ROCKET MOTORS

by

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Abstract

The USAF MINUTEMAN ICBM Transportation and Handling Test Program involves vibration testing of full scale motors. A major problem in vibration testing of large solid propellant motors is developing a method of embedding accelerometers in the viscoelastic propellant. The accelerometers are needed to determine experimentally the dynamic response of the propellant during the environmental tests, and to verify the motor's dynamic analysis.

The engineering analyses and experimental tests employed by Thiokol Chemical Corporation to develop the accelerometer installation method is the subject of this paper. The results of the instrumentation, and the degree to which the desired results were achieved, are discussed.

Extensive engineering studies were made to determine the minimum number, location, and type of accelerometers required to describe the dynamic response of the propellant. A technique was developed for controlling the position and orientation of the accelerometers when embedded in the motor propellant. A laboratory research program was conducted to develop reliable bond joints.

The configuration finally selected uses 24 triaxial accelerometers, of which 14 are embedded in the propellant and 10 are mounted on the propellant surface. The accelerometer and cable assemblies are precast in propellant wedges, which are bonded in the case prior to casting the motor. Piezoelectric accelerometers were selected in order to meet the dynamic response, safety, density, and temperature specifications.

As a final verification of the design concept, and to check out special manufacturing techniques and tooling, a subscale motor was successfully cast with accelerometers embedded in the propellant. This was accomplished prior to casting a full scale motor. Both the subscale and full scale motors were used in the vibration testing program.

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Thiokol Chemical Corporation utilized a new vibration facility for performing these vibration tests. This facility is equipped with electrodynamic and electro-hydraulic exciter systems that have combined capabilities of sinusoidal force outputs from 0 to 200,000 vector force pounds, and frequency capabilities from DC to 2,000 cycles per second.

With the design concept developed for internally instrumenting solid propellant rocket motors, it is technically feasible to static fire these motors after the vibration tests are completed as final confirmation of the motor integrity. This capability was a secondary program objective.

Introduction

In the initial stage of the MINUTEMAN development program, the capability of the Stage I MINUTEMAN motor to withstand a prolonged transportation and handling environment was unknown. The chance that transportation and handling problems might occur as a result of vibration, shock, structural discontinuities, and localized loading required that the effect on reliability be investigated. In simple beams, these problems normally lend themselves to analytical study and analysis.

The Stage I motor, however, is a highly complex structure comprised of a thin-steel outer shell approximately 5 ft in diameter and 20 ft long, with a thick bonding liner. Key areas inside the case are insulated with a rigid insulating material bonded to the shell. The case is filled with a large mass of viscoelastic propellant having a star-shaped core chamber through the center. With such a composite structure, the mechanical properties of which are either unknown or vary from specimen-to-specimen, classical beam analysis becomes inadequate in describing the response of the motor to a dynamic input.

Because of the specialized nature of this problem, a consulting service in Applied Mechanics performed an analysis and predicted the dynamic response of the Stage I motor when subjected to transportation and handling environments.

To verify this analysis by tests, Thiokol Chemical Corporation conducted road, air shipment, and obstacle course tests to determine how well the motor would withstand actual field conditions. Although a great amount of useful information was obtained from these tests, no satisfactory means was found to control the test environment over the entire frequency range and at the acceleration levels required to check the analytical predictions or to determine the dynamic response of the motor. The frequency excitation levels were so low in value that the motors tested by these methods responded essentially as a rigid body. No fundamental frequencies or mode shapes were measurably excited.

To determine the fundamental frequencies, mode shapes, and propellant response, and to check the analytical predictions, Thiokol designed and constructed

a vibration test facility at the Wasatch Division with the capability of testing the full scale Stage I MINUTEMAN motor.

To fully describe the behavior of the motor, the propellant response was required as well as the case response. Engineering studies were conducted to establish the minimum number and location of accelerometers required to determine the dynamic response of the propellant during the vibration tests. A method of embedding these accelerometers was developed that enables the accelerometers to be fixed in prescribed locations during propellant casting. No adverse dynamic effects occurred on the motor or propellant from the embedded accelerometers and cable assemblies.

Discussion

One of the major problems associated with this program was trying to determine the number and corresponding locations of accelerometers required to describe the dynamic behavior of the propellant during vibration tests.

Joint studies by Space Technology Laboratories, Dyna/Structures, Inc, and Thiokol indicated that the dynamic response of the Stage I propellant grain could best be determined by embedding three rows of accelerometers in the propellant at each of six linear cross-sectional stations within the motor (Figure 1).

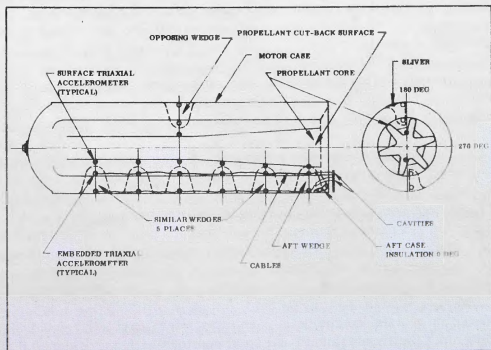


Figure 1. Internal Instrumentation Design Concept

Transducer Selection

After the number and location of the accelerometers were determined, an accelerometer had to be selected that would meet the specifications for dynamic response, temperature, density, and safety. The general specifications for the accelerometers were:

1. Performance - The accelerometers had to contain three sensing elements in a single mounting case, with three mutually perpendicular axes of sensitivity. The sensing elements had to be capable of measuring minimum and maximum sinusoidal accelerations of 0.1 and 50 g peaks, respectively, applied in the direction of the particular axis or axes of sensitivity. The linearity of the response of the sensing elements had to be within ± 1 percent at any frequency between 2 and 2,000 cycles per second. The accuracy of the sensing elements at any frequency between 2 and 2,000 cps within the specified acceleration range, had to be within ± 5 percent. The phase shift between the applied stimulus and the electrical output of the sensing elements could not exceed 1 deg at any frequency or acceleration level within the specified ranges. The distortion of the output wave-form of the sensing elements could not exceed 5 percent of the fundamental signal of an applied stimulus. Cable connectors for the three axes of sensitivity for each accelerometer had to be located on a common side.

2. Safety - Piezoelectric self-generating accelerometers, suitable for embedding in live propellant, were used. The nature and low level of the electrical signal generated by this type of accelerometer eliminates the danger of inadvertently igniting the live propellant.

3. Density - The density of the accelerometer had to be the same as the live propellant, $1.7 \text{ gm} \pm 0.1 \text{ gm}$ per cubic centimeter. The accelerometer center-of-gravity had to be located at the geometric center.

4. Temperature - An accelerometer operating temperature range between -20°F and $+200^\circ\text{F}$ was required.

The output response of the sensing elements at temperatures other than 70°F had to be within ± 5 percent of the reference output response at 70 degrees. (The response output of the elements was measured with a $2,000 \pm 200$ picofarad cable). The accelerometer had to withstand temperature cycles up to 300°F without detrimental effects or impairments.

A Gulton triaxial piezoelectric accelerometer, part number TA 320106, was selected to meet the requirements and specifications within a designated time limit. Laboratory tests indicated that these accelerometers could be bonded in the propellant by priming the aluminum outer jacket of the accelerometer with Epon 812 (Epoxy, bond conditioner).

Transducer Cable Selection

An interconnecting electrical cable, compatible with the piezoelectric accelerometer, was selected. Cable requirements were:

1. The cable outer covering or insulation had to be fabricated from a material that could be readily bonded to the live propellant.
2. The overall diameter of the cable had to be kept to a minimum to prevent overstressing the surrounding propellant.
3. The electrical capacitance of the cable could not exceed 40 picofarads per foot of cable.
4. The noise level could not exceed 1 mv peak-to-peak. The noise level was measured by vibrating a 10 ft section, with an initial 3 1/2 in. sag at the center, at 25 cps with a 1 in. double amplitude. During these tests, one end of the cable was connected to the exciter and the other end terminated at a 100 mego impedance source.

After electrically testing cables from several manufacturers, polyvinyl chloride, silicon rubber, and wrapped Teflon jacket materials were selected. An extensive laboratory testing program was conducted to aid in selecting the more suitable cable covering for bonding to live propellant, other factors being equal. A Gulton cable with a silicon rubber jacket, primed with UF-3170 (Silicon Primer), proved to be most compatible.

Accelerometer and Cable Assembly Verification Tests

The following problems associated with the use of the accelerometer and cable as an assembly had to be resolved:

1. What effect did the dielectric properties of live propellant have upon the characteristics of the accelerometer and cable?
2. What type of cable-to-accelerometer connection configuration was best (connector or integral connection)?
3. What effect would propellant shrinkage have on the accelerometer and cable assemblies during the cure cycle?
4. What would be the dynamic transmissibility of the accelerometer and cable assemblies when they were embedded in live propellant?

Verification Tests

In order to resolve these problems, accelerometer and cable assemblies were embedded in 10 in. propellant cubes for dynamic testing. For one type of specimen, the cable assemblies were routed directly out of the propellant. In a second type of specimen, the cables were coiled prior to routing out of the propellant to determine the effects on accelerometer output when loads were introduced into the cables. The test specimens were bonded to an aluminum plate that also served to attach the fixture to the exciter table. Each of the specimens underwent resonance search tests from 10 to 500 cps at a 1.0 g acceleration level. The samples were also vibrated at 500 cps and 3.0 g for 20 minutes. Side loads were applied to the cable assemblies to evaluate methods of connecting the cable assemblies to the accelerometers.

The maximum frequency at which meaningful data were obtained was 500 cps, due to the frequency limitations of the exciter table. No changes occurred in accelerometer response when side loads were applied to the cable assemblies for either type of specimen. Direct routing of the cables from the specimen was selected as the simpler method of the two. After the verification tests were completed, the specimens were sectioned and inspected for bond separations. The bonds were good in all cases. The dielectric properties of the propellant had no effect on the accelerometer and cable assemblies. Thermal contraction of the propellant during cooldown from the curing temperature did not affect the bond joints or performance of the accelerometer and cable assemblies.

Safety Tests

After final selection of accelerometer and cable assemblies, safety tests were conducted to make sure that the live propellant could not be ignited by connection of the embedded accelerometer cable leads to electrical power supplies. Two types of specimens were prepared for these tests. The first type consisted of small samples of live propellant in which shorted accelerometer cables were embedded. In some of the specimens, the inner conductors were shorted; in others, the shield conductors were shorted, while still others had the inner conductor shorted to the shield conductor.

The second type of specimen was a small sample of live propellant with accelerometer and cable assemblies embedded. After the propellant had cured, the specimens were brought to an ambient temperature of about 80°F prior to testing.

The tests consisted of connecting the cables directly to 115 vac, 220 vac, and 440 vac power sources. The propellant did not ignite, indicating that no hazardous condition exists from the electrical power sources available in the vibration facility.

Embedment Technique

In developing a method of installing a line of three accelerometers at six cross sections along the motor, these criteria were observed:

1. The accelerometer installation and cable routing could not change the dynamic characteristics of the propellant.
2. The accelerometer axes of sensitivity must be oriented within $\pm 1/4$ in. and $\pm 2-1/2$ deg of each other and must be supported by propellant only.
3. The propellant must be cut back without cutting the accelerometer cables.
4. As a secondary objective, the motor would be static test fired after completing the dynamic tests.

Two of the three accelerometers and cable assemblies in each cross section were precast in propellant wedges, which were bonded into the case at each of the linear motor stations prior to casting the propellant. The position and orientation of the accelerometers in the propellant wedges were controlled during the wedge fabrication and were in the same relative position for each wedge (Figure 1).

The wedges were installed so that a common edge of each accelerometer was located on the flat surface of the wedge. The wedges are located linearly in the case by measuring from a common reference point on the motor case. The flat surfaces of the wedges are angularly aligned in the case prior to bonding them in place.

The third accelerometer and cable assemblies required at each of the linear motor stations were installed on the propellant surface prior to attaching the aft closure. The accelerometer orientation was controlled by the mounting blocks used to install them. The mounting blocks, fabricated of balsa wood, were used to orient the accelerometers. The accelerometer and cable assemblies were easily removed after the dynamic tests were completed by shearing the mounting blocks close to the propellant surface (Figure 1).

The cable assemblies from the wedge located at the midpoint of the motor, 180 deg from the continuous row of wedges along the 0 deg target side of the case, were routed circumferentially around the inside of the case. These cables intersected with the cables from the lower accelerometers, which were embedded in the continuous row of wedges. From this point, the cables were bundled together and were routed to the aft end of the motor (Figure 1).

The cable assemblies from the upper accelerometers, which were embedded approximately 11.5 in. inboard from the case, were routed parallel to the motor longitudinal centerline. The cables were spanned, telegraph style, between wedges and were bonded to the flat face of each wedge (Figure 1).

The cable assemblies from the lower accelerometers, which were embedded approximately 3 in. inboard from the case, were routed along the lined case to the aft end and were bonded to the case liner. All of the cables were tightly bundled before being bonded in position.

By using the vacuum casting process, no voids occurred around the cable bundles during the propellant casting and cure processes. By routing the cables in the manner described, the feasibility of static firing the motor was enhanced, because the flame front would reach the cables in each cable bundle at the same time, and no radial path was provided for a burnthrough or increased burning area (Figure 1).

The propellant is machined to a specified configuration to provide a plenum chamber (Figure 1). This is called a cutback operation. The propellant cutback operation was performed successfully by providing cavities into which the cable assemblies could be placed during this operation. After the cutback operation was completed, the cable assemblies were routed out the aft end of the motor and the cavities around the cable assemblies were filled with propellant (Figure 1).

Bond Joint Tests

Laboratory tests were conducted to evaluate the bond joint between cured propellant wedges and uncured propellant. By priming the cured propellant with Epon 812 prior to the casting operation, the bond joint between cured and uncured propellant was as strong or stronger than the parent propellant. Detailed studies also were conducted to make sure that the properties of the propellant did not change when exposed to three temperature-curing cycles at 135°F of 96 hr duration each. These temperature cycles were required to cure the propellant wedges, the case propellant, and the propellant used to fill the accelerometer cable cavities. Laboratory tests proved that the propellant could withstand these temperature cycles with no physical property changes.

Laboratory tests were also conducted to determine a reliable bond joint between the propellant wedges and the case liner. A UF-2123, ambient-cured liner, was developed and evaluated for bonding cured TP-H1011 propellant on UF-2121 liner. The pot life of UF-2123 liner after deaeration is 4 hr at 75° ± 5°F. Cure times are 96 hr at 75°F, 9 hr at 135°F, and 5 hr at 170°F.

Testing of UF-2123 liner was programed to include all phases of bonding cured propellant wedges in lined motor cases, including preheat prior to casting, vacuum casting conditions, and extended cure at 135°F. Tensile, shear, and fatigue tests were conducted on sample bond joints, utilizing deaerated UF-2123 liner. In all cases, the bond joint had greater strength than the propellant. Other test samples were prepared, using the same systems curing and testing conditions, except the UF-2123 liner was not deaerated prior to application. When these samples were

tested, they gave lower values and swelled during the vacuum phase of testing. In all cases where the UF-2123 liner was not deaerated and tested under vacuum, failure occurred in the UF-2123 liner.

Additional test specimens were fabricated to simulate the bond joint between the propellant wedges and case liner. Various loads were applied to these test specimens when exposed to motor processing environment, and in all cases the bond joint was good.

The test data verified that UF-2123 liner was an adequate adhesive for bonding cured TP-H1011 propellant to cured UF-2121 liner. These bond joints were satisfactory for either bayonet-type casting or vacuum casting; however, when they are used with vacuum casting, the UF-2123 liner must be deaerated prior to using.

Special Equipment Requirements

Propellant Wedge Molds

The propellant wedges were designed to support two accelerometer and cable assemblies in a specific orientation and location during casting operations. The final wedges weighed approximately 45 lb and were approximately 14 by 11 by 15 inches.

Fiberglass molds were designed and built to fabricate these propellant wedges. Three different mold configurations were built to meet all the requirements for instrumenting a motor. The first configuration was for the case wedge, the second configuration was for the aft case wedge, and the third configuration was for the opposing case wedge (Figure 2 and reference Figure 1).

The first configuration excluded the case slivers at that location. The slivers were deleted because the close installation tolerance between wedges could be controlled more easily without them. The deletion of this one sliver will not appreciably affect the dynamic response of the propellant or motor (Figure 3 and reference Figure 1).

The second configuration is designed to fit over the aft case insulation and contains the cable cavity connections (Figure 4 and reference Figure 1).

The third configuration fits over the sliver on the opposite side of the motor. Because only one wedge was installed on this side of the motor, the sliver did not interfere with installation tolerances (Figure 1 and 2).

The exact position and orientation of the accelerometers in the propellant wedges were accomplished with holding fixtures specifically located on the wedge mold. The accelerometer and cable assemblies were held in position by these fixtures while the propellant was being cast around them (Figure 5).

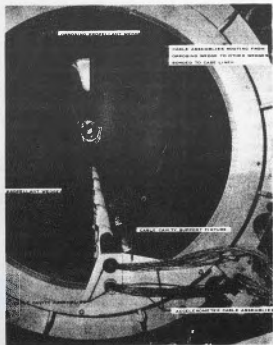


Figure 2. Propellant Wedges Installed in Lined Motor Case



Figure 3. Typical Propellant Wedge Installation

The major problem associated with the wedge mold design was developing a technique to remove the propellant wedges from the molds after they had cured. Laboratory tests indicated that a conventional rubber-type parting compound would contaminate the propellant wedge and would prevent a good bond joint between the cured and uncured propellant. Attempts to remove the wedges from the mold with air ports in the molds and suction cup pulling devices proved to be unsatisfactory. The purpose of the air ports was to provide a means of breaking the bond between the wedge and the mold. This technique proved unsatisfactory because the air would escape along a very narrow path and would not cause separation of the wedge and mold over a sufficiently large area. The suction cups were satisfactory, but no separation occurred between the wedge and mold. This removal problem was overcome by lining the molds with Teflon tape prior to casting the wedges. When used in conjunction with the air ports, the Teflon tape acted as a good parting material, and the wedges could easily be removed from the molds. No contamination problems occurred when Teflon tape was used.

Cavity Assemblies and Support Brackets

In order to perform the cutback operation, a cavity was provided in which the accelerometer cable assemblies could be safely placed. After performing calculations and experimental tests on different methods of coiling the accelerometer cables, a cavity approximately 15 in. long by 2-1/2 in. in diameter was found to be satisfactory. These cavities were formed by casting the propellant around cavity assemblies (aluminum tubes). After the wedges had been installed in the case, the accelerometer cable assemblies were routed from the last wedge into the cavity assemblies, and the joint between the cavity assemblies and the wedge were sealed (Figures 6 and 7).

The cavity assemblies were wrapped with Teflon tape to simplify removal after the propellant had cured. A support bracket was designed and fabricated to hold the cavity assemblies in position during propellant casting. This support bracket restrained any axial loading of the cavity fixtures due to buoyancy when the fixtures were submerged in uncured propellant (Figure 4).

Manufacturing and Processing Details

Preparation of Accelerometers and Cable Assemblies

The accelerometers were all calibrated electrically, and the calibration results for each axis of sensitivity were recorded. Prior to embedding the accelerometers in propellant, they were primed with Epon 812 Liquid Epoxy Resin to insure a good bond with the propellant. Cable assemblies for each accelerometer axis of sensitivity were fabricated and identified with a coding number. The coding numbers were required to identify the embedded accelerometers and corresponding axis of sensitivity after completing the casting operations. The cable assemblies were

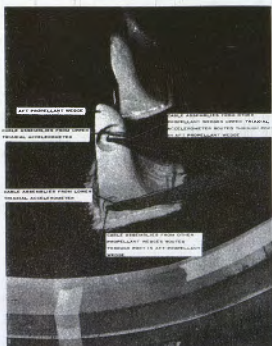


Figure 6. Cable Routing at Aft Propellant Wedge



Figure 7. Installation of Accelerometer Cables in Cavity Assemblies

connected and safety wired to the accelerometer. The cable assemblies were primed with UF-3170 sealant to insure a good bond when the assemblies were embedded in the propellant.

Installation and Electrical Tests of Accelerometers and Cable Assemblies

The accelerometer and cable assemblies were installed in the wedge and were checked electrically prior to casting the wedges. These electrical tests insured that the accelerometers or cables were not shorted or broken prior to embedding them in the propellant wedge. If any defect had existed, repairs or replacements at this stage of the process easily could have been made.

The accelerometer cable used was unique in that it had nearly zero series resistance and a distributed capacitance of 33.6 picofarads per foot of cable. With this capacitance characteristic, the amount of capacitance a cable of a given length will have is known. By adding the capacitance of the accelerometer, the total capacitance of any accelerometer-cable combination is known. One of the electrical tests utilized was to measure the capacitance of the accelerometer-cable combinations. If the cable or accelerometer circuit is broken, it is easily detected and the specific location of the break is known within inches.

An additional electrical check was required because the cable or accelerometers could have had a high resistance short that was not detected by the capacitance test. By putting a 50 vdc input into the accelerometer-cable combinations and measuring the resistance between the inner conductor and outer shield, any existing shorts were detected.

Propellant Wedge Processing

After completing the electrical checks and lining the wedge molds with Teflon tape, the wedges were cast with propellant. Two small individual propellant batches were used to cast the propellant wedges. The propellant wedges were bayonet cast instead of vacuum cast to permit manual control of the cable routing and the flat surface of the wedge. After the wedges were cast, they underwent a cure cycle of 135°F for 96 hours.

After curing, the propellant wedges with the embedded accelerometer and cable assemblies were removed from the casting molds. The propellant wedges were individually X-rayed to verify that no voids or air pockets existed.

Installation of Propellant Wedges and Cable Assemblies

The propellant wedges initially were installed dry, positioned, and aligned. With the wedges in the proper position, the case liner was masked off so that the

wedges could be quickly installed in the correct location after the bonding compound was applied. Because of the confined work area, only one wedge was handled at a time and always the extreme aft wedge. Therefore, after the locations were masked off, all the wedges were removed prior to permanently installing them with bonding compound (Figures 8 and 9).

As each wedge was installed with bonding compound, its alignment was checked visually. After the opposing wedge on the 180 deg axis of the case was installed and aligned, the UF-2123 bonding compound was allowed to cure for 96 hr at ambient temperature (75°F). After the bonding compound on this wedge had cured, the motor was rotated 180 deg and the remaining wedges were installed in the same manner. The cable assemblies from the opposing wedge then were routed circumferentially around to the other wedges and were bonded to the case liner with UF-2123 liner. The motor was rotated as required during this operation. The cable assemblies from this wedge and the bottom cable assemblies from all the other wedges were routed along the case and into the lower cavity assembly (Figure 1).

An electrical check was made before bonding the cables to the case liner to insure that the cables had not been damaged during the processing, X-ray, and installation operations. Any damaged cable assemblies were repaired prior to bonding them in place.

The lower cable assemblies were bonded in place, and the point between the lower cable cavity assembly and the aft wedge was sealed with UF-2123 liner (Figure 4).

After the lower cable assemblies were bonded in place, the motor was rotated 90 degrees. The upper cable assemblies were bundled and routed along the wedge and into the upper cavity assembly. Rotating the case made it easier to bond the cable assemblies to the propellant wedges (Figure 10).

An electrical check was again conducted before bonding these cables to the propellant wedges.

The upper cable assemblies were then bonded in place, and the joint between the upper cable cavity assembly and the aft wedge was sealed with UF-2123 liner (Figure 4).

All of the installed propellant wedges were primed with Epon 812 to insure a good bond between the cured propellant wedges and the remainder of the motor propellant.

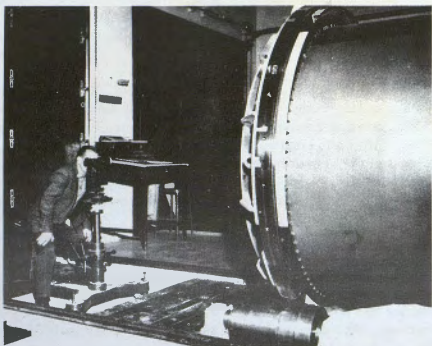


Figure 8. Propellant Wedge Alignment Operation

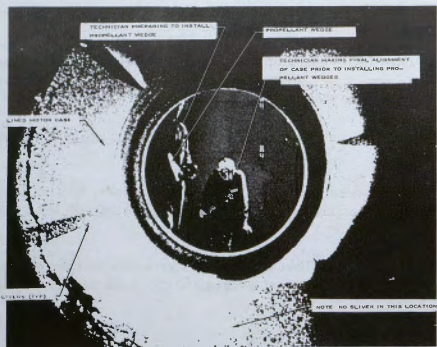


Figure 9. Propellant Wedge Installation

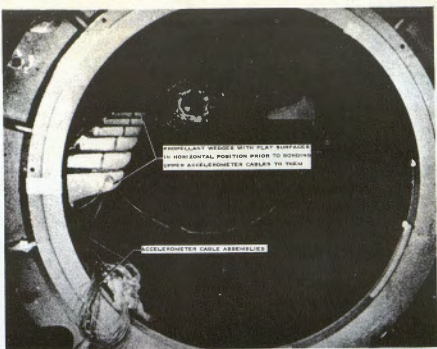


Figure 10. Positioning Upper Accelerometer Cables Prior to Bonding

Wedge Installation Tests

Before casting a full scale motor with internal instrumentation, verification tests were performed utilizing an aft subassembly. The bond joint was checked by applying weights of 27, 18, and 10 lb to the propellant wedges installed in the aft subassembly. The 27 lb weight, the most severe condition, reduced the safety factor from 8.32 to 2.83 (Figure 11).

The weighted wedges were exposed to temperature and vacuum conditions similar to those encountered during full scale motor casting. No failures occurred during this temperature-vacuum cycle; therefore, the weights were removed and the subassembly was cast with propellant as a final confirmation of the design concept. The X-ray and visual inspections of this specimen after the propellant had cured proved conclusively that the concept was technically sound.

Casting and Curing Motor

After successfully completing the wedge installation tests in the aft subassembly, the full scale motor was prepared for processing. The wedges were installed in the lined case and the motor was prepared for casting according to normal operating procedures. The casting core, the vacuum casting bell, and other miscellaneous equipment were installed (Figure 12).

The motor casting and curing operations were accomplished with no problems or unusual occurrences. After curing, the cable cavity assemblies were removed, and the accelerometer cables were coiled and placed in the cavities below the cut-back depth. The motor was cut back in accordance with normal processing procedures.

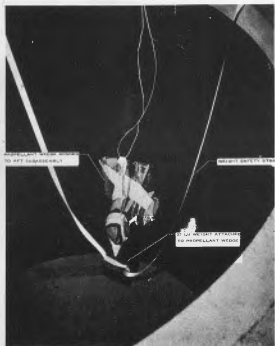


Figure 11. Weight Installation on Propellant Wedge

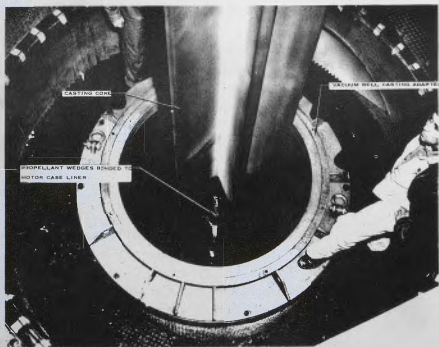


Figure 12. Casting Core Installation

The accelerometer cable assemblies then were uncoiled and routed directly out of the cavities. The cavities were primed with Epon 812 Liquid Epoxy Resin prior to filling them with TP-H1064 propellant. This propellant is identical to TP-H1011 except that it has spherical aluminum particles instead of coarse ground aluminum particles. This propellant is less viscous in the uncured state than TP-H1011 and does not develop as many voids when filling small cavities. After filling these cavities, the motor was recycled at 135°F for 96 hr to cure the propellant.

Inspection and Final Processing

The motor was given a complete X-ray and ultrasonic inspection prior to installing the aft closure and nozzle assemblies. No voids or cracks were revealed in the propellant or around the wedges or cable assemblies.

Final electrical checks showed that all the accelerometer and cable assemblies were completely functional.

Example of Results

Longitudinal Mode of Vibration

The first longitudinal resonance of the solid propellant rocket motors tested occurred at 37 cps. The corresponding mode shape and phase relationships shown in Figure 13 indicate that the predominant response of the case and propellant is that of a fixed-free rod with a slightly coupled propellant thickness shear mode.

The second longitudinal resonance of the solid propellant rocket motors tested occurred at 70 cps. The corresponding mode shape and phase relationships shown in Figure 14 indicate that the predominant response of the case and propellant is that of a free-free propellant thickness shear mode with a slightly coupled case rod mode.

Transverse Mode of Vibration

A typical example of the mode shapes assumed by a rocket motor case and different levels of the propellant while vibrating the motor at its simply supported beam bending frequency, which is an antiresonant condition is shown in Figure 15.

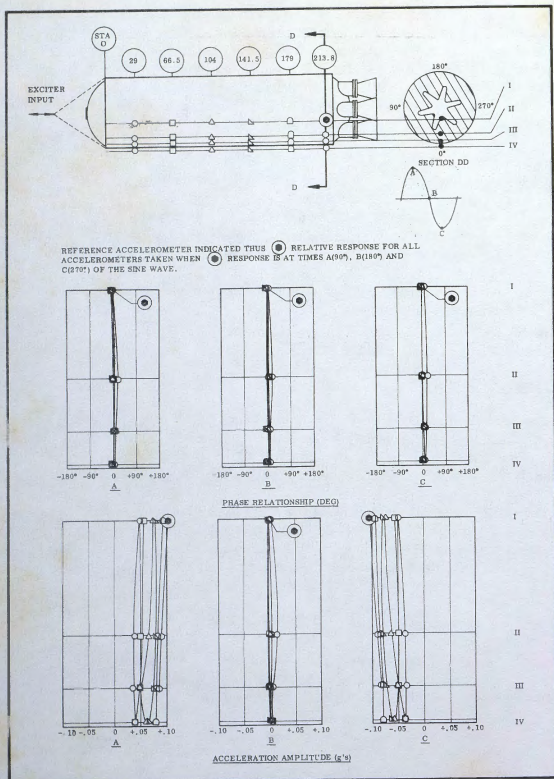


Figure 13. Longitudinal Response of Motor Case and Propellant at 37 cps

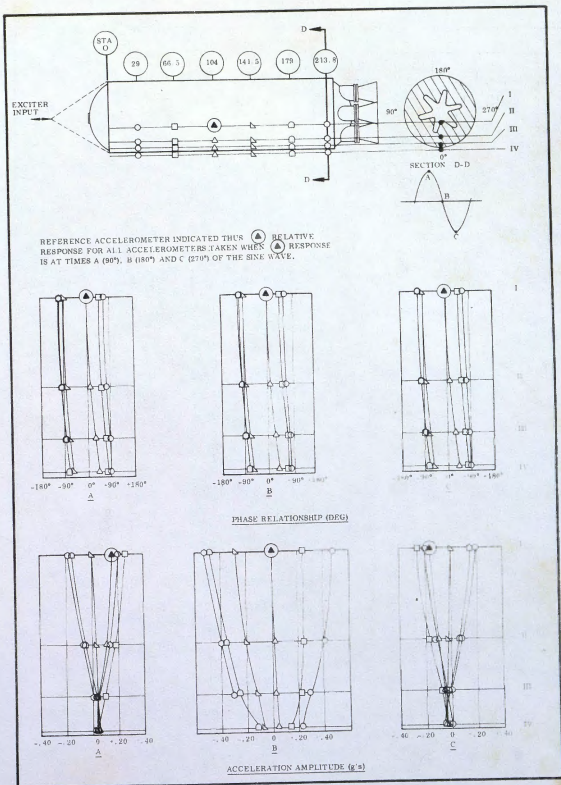


Figure 14. Longitudinal Response of Motor Case and Propellant at 70 cps

NOTES:

1. TRANSVERSE TEST SET-UP MOTOR "Y" JOINTS CONSTANT FORCE OF 8,000 LB/EXCITER
2. MODE SHAPE SHOWN IS WHEN REFERENCE ACCELEROMETER \odot RESPONSE IS MAXIMUM
3. \circ DENOTES ACCELEROMETERS LOCATED AT 270 DEG SIDE OF MOTOR CASE
4. \triangle DENOTES ACCELEROMETERS LOCATED AT 90 DEG SIDE OF MOTOR CASE
5. \square DENOTES ACCELEROMETERS LOCATED AT PROPELLANT STAR POINT (SURFACE)
6. \diamond DENOTES ACCELEROMETERS EMBEDDED IN PROPELLANT STAR VALLEY
7. \ominus DENOTES ACCELEROMETERS EMBEDDED IN PROPELLANT, ADJACENT TO CASE

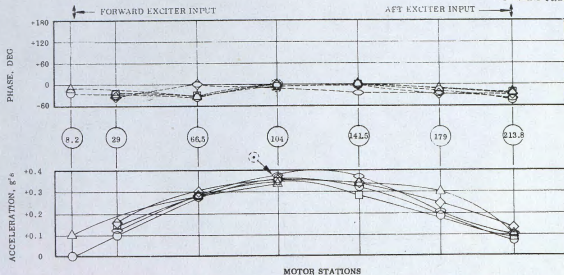
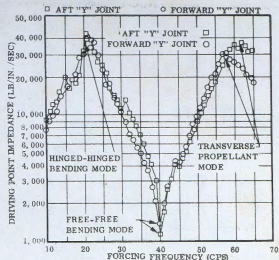


Figure 15. Transverse Response of Motor Case and Propellant at 21 cps

The technical results of the vibration tests are not presented in this paper. The typical examples are included only as an illustration of what may be accomplished with this method of instrumentation.

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