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ABSTRACT

An experimental program is described in which the bending and longitudinal dynamics of structures simulating solid-propellant rocket motors are being studied. The structure is considered to be a cylindrical grain of solid propellant to which is bonded a thin steel case. Vibrations of the empty steel cylinder suspended in a free-free condition are studied first. Secondly, a similar steel cylinder loaded with an inert propellant grain will be studied to determine the effect of the propellant on the vibrations of the case. Additional experiments to determine the viscoelastic properties of the propellant required for an analysis of the structure are discussed.

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ILLUSTRATIONS

1. INTRODUCTION

One of the major problems associated with the development of large missiles is the design of a stable autopilot. In general the degree of complexity and, as a consequence, the reliability of an autopilot depends largely on the bending dynamics (frequencies, mode shapes, and damping) of the missile being considered. It is, therefore, essential that the autopilot designer have available accurate knowledge of these quantities. In addition to the autopilot requirements, accurate knowledge of the frequencies, mode shapes, and damping for both bending and longitudinal motions are needed for dynamic loads analyses and staging studies.

In order to calculate, in a practical manner, mode shapes and frequencies of a missile, it is necessary to make certain simplifying assumptions concerning the dynamic behavior of the missile. When considering longitudinal and bending dynamics, it is generally assumed that the missile behaves like a nonuniform beam. The validity of this assumption has been established for some structural configurations by dynamic tests on actual missiles. These tests have also provided some data on the amount of damping that is associated with missile structures. However, no tests of a similar nature have been performed on solid-propellant missiles of the size of MINUTEMAN.

From the point of view of dynamics, the unique feature of solid-propellant missiles is that, in general, the propellant is bonded to a portion of the airframe, i.e., the engine casings form a part of the airframe. For a missile the size of the MINUTEMAN, the engines, which comprise virtually all of the airframe, are essentially thin-walled cylinders bonded to a large mass of propellant whose mechanical properties are vastly different from those of the cylinder. In view of the high ratio of propellant mass to structural mass which is characteristic of these large engines, it is clear that the propellant will have a major effect on the dynamic behavior of the missile airframe. Consequently, this experimental program is being carried out to determine:

(a) The dynamic behavior of a configuration representative of large solid-propellant engines.

(b) The validity of dynamic models that have been proposed.

(c) The damping supplied by the propellant.

The specific objectives of this program are:

(a) The determination of the effective stiffness, shear rigidity, and mass of solid-propellant-like materials when bonded to a thin, metal casing and undergoing bending or longitudinal vibrations.

(b) The determination of the structural damping provided by solid-propellant-like materials.

(c) The determination of the effect of internal pressurization on the structure's dynamic characteristics.

2. TECHNICAL PROGRESS

A. Phase 1 - Bending Vibrations of an Unloaded Cylinder

The purposes of this phase were to determine the vibrational characteristics of a thin, circular cylindrical metal shell supported in the free-free condition and to establish the detailed experimental techniques to be used throughout the remainder of this program. The results of the empty cylinder tests were to be used as a basis of comparison for later experiments (Phase 2) involving similar cylinders loaded with an inert propellant.

The dimensions chosen for the cylinders to be used in these tests were a length of 8 feet, an internal diameter of 6 inches, and a wall thickness of 0.032 inch. These cylinders, rather than being scaled from any existing rocket motor casing, were chosen so as to yield a model whose natural frequencies would be within the range of available instrumentation, would not be too cumbersome to manipulate in the laboratory, and whose radius-to-wall-thickness ratio was similar to that of an actual motor.

Four cylinders were rolled and seam welded of 410 stainless steel. The tolerance placed on ovality was ±0.032-inch wall thickness (or ±1 wall thickness) and a maximum axial bow of 0.064 inch was specified. The cylinders were provided with threaded end closures containing O-ring seals, thereby rendering them air tight.

In order to simulate adequately free-free vibration modes of the models, it was decided to suspend them in the horizontal position by vertical wires attached to the end caps. The cylinders could then be vibrated in a horizontal plane and be expected to meet with a minimum of resistance from external supports. Figure 1 shows a cylinder suspended in this manner

Two shakers were attached to the specimen, each driving horizontally into an end cap. Light struts with flexure pivots at each end were used as the connecting link between shaker and tube (see Figure 2). The electrical input to he shakers was made to be easily switched from an in-phase condition for exciting even order axial bending modes to a 180-degree, out-of-phase condition for the odd order modes It was discovered that the 25-force-pound shakers were sufficient for the empty tube studies, but it is anticipated that the larger 250-pound units will be required for the loaded cylinder studies.

Considerable time was devoted in designing the instrumentation to be used for these studies. At first it was felt that the tube vibrations could be sensed by a number of accelerometers located at appropriate stations along the tube. The acceleration levels at these stations could then be plotted simultaneously on a multichannel oscillograph However, it was discovered that fixing an accelerometer to the tube wall (the total weight of the accelerometer and mounting pad being about 20 grams) resulted in local deformations that were serious enough to introduce considerable error in the true acceleration level at that point.

In order to load the tube wall more lightly and to avoid this difficulty, a probe type velocity pickup was tried This device was apparently successful in indicating true vibration levels, but was limited in frequency response to an upper limit of about 800 cps However, the fact that this transducer only required that a spring-loaded probe be placed against the tube suggested the idea of sliding the probe along the tube to monitor continuously vibration level

Accordingly, a track was laid parallel to the tube on which was placed a sliding pedestal to support the probe-type transducer An unbroken steel belt encircling pulleys at either end of the track was attached to the pedestal to provide a mechanical positioning device Finally, a slider on the pedestal was made to contact a linear slide wire running the length of the track, thereby acting as a voltage divider to give an electrical indication of the axial position of the probe on the tube.

A circumferentially running track was next fixed to the pedestal on which a carriage holding the pickup could be run so as to move the pickup around the tube. A 10-turn potentiometer connected to the circular track by a belt gave an electrical indication of the position of the probe around the tube. See Figure 3 for the details of this device.

The voltage from either of these position indicators could be applied to the x input of an x-y plotter, while the transducer output voltage was rectified and filtered and applied to the y input of the plotter to yield directly mode shape plots for any normal mode vibration of the tube. That is, the vibration intensity level of the tube wall along any axially or circumferentially running line on the tube may be plotted directly.

Recent tests, using a microphone instead of the probe-type velocity transducer as a vibration pickup, have shown that the microphone, while being somewhat sensitive to external noise, does not place an upper limit on the frequency. Also, it was found that sliding the probe of the velocity pickup along the tube introduced considerable noise in the signal

In Figure 4 are shown typical mode shape plots obtained by the method described above. It can be seen that there are four nodal lines running circumferentially around the tube (two of which are near the ends of the tube) and two nodal lines directed axially along the wall. These conclusions are made by realizing that a minimum point on the curves indicates a node and that the microphone is sensitive to displacements normal to the tube wall Curve ② - ⑤ - ②, a circumferential survey at Position ② along the tube axis, shows that the nodal points observed from Curve ① - ② - ③ - ④ are truly lines of zero displacement encircling the tube. Curve ③ - ⑥ - ③ illustrates the fact that the tube cross section remains circular and is merely undergoing a translation in the horizontal plane for all other axial positions.

Few such data for the empty cylinder have been taken, but it is expected that since the instrumentation has been shown to work so well, all the necessary runs with the empty cylinder can be completed shortly.

B. Phase 2 - Bending Vibrations of a Cylinder Loaded with Inert Propellant

One of the empty cylinders was filled with an inert propellant (DP-16 simulating third-stage MINUTEMAN) by Aerojet and is now ready for testing. The grain which is bonded to the case has a cylindrical perforation of about 2 inches in diameter.

C. Phase 3 - Propellant Mechanical Property Tests

Soon after the program was begun it was realized that no clear definition of the dynamic mechanical properties of solid propellants was available, but it was known that this material was viscoelastic in nature and could therefore be expected to contribute to the damping of the structure. For these reasons a series of experiments to determine the dynamic complex shear compliance of an inert solid propellant typical of that to be used in the model motor studies was begun.

These tests were designed to be relatively simple experimentally and also of such a nature as to make an analytic study of the configuration possible. Thus, a twofold purpose would be served the dynamic properties of the material would be measured, and experience would be gained in solving problems dealing with a viscoelastic material.

The first model chosen was that of a circular plate of the inert propellant (DP-16) bonded at the outer edge to a steel ring. A mass was clamped at the center of the disc (see Figure 5). Axisymmetric vibrations of the plate could be excited by shaking the edge of the disc. Relative displacements and phase differences between the center and the edge of the disc were detected by the use of accelerometers attached to the center mass and the cup-like device connecting the edge of the disc to the shaker.

Experimental data covering the range of 75 cps to about 1500 cps were obtained for several values of center mass and plate thickness. In Figure 6 are shown a typical set of relative amplitude and relative phase angle curves. Pending completion of the analytical phase of this problem these data will be used to obtain the dynamic mechanical properties of the material over the frequency range studied in the experiment.

The second experiment that was devised was really a simplification of the first from the analytic standpoint. A long, hollow circular cylinder of the same inert propellant was bonded to a steel case on its outer surface and to a circular steel rod on its inner surface. Axisymmetric longitudinal vibrations could then be excited by shaking the steel case longitudinally. Similar observations could be made of the motion as in the case of the circular plate. The apparatus for this experiment has been set up, but as yet no results have been obtained.

For the purpose of comparison of the results obtained in the two above mentioned experiments, a contract was made with the Atlantic Research Corporation for them to test a sample of the same inert propellant on their Fitzgerald apparatus. This device, which is the industry accepted standard, measures the complex dynamic shear modulus of a viscoelastic material over the frequency range 25 to 5000 cps within an accuracy of 1 per cent or less. In Figure 7 are shown the results of their test runs at two temperatures.

From these results it can be seen that the imaginary or loss component of the shear modulus is about 20 per cent of the real or elastic component. In other words, nearly 20 per cent of the energy supplied to a dynamic system composed of this material would be dissipated in the material. It is therefore to be expected that the propellant will contribute quite heavily to the damping of a solid-propellant motor.

3. TECHNICAL PLANS

A. Phase 1 - Bending Vibrations of an Unloaded Cylinder

Identification will be made of as many mode shapes as possible in the unloaded cylinder at several values of internal pressure up to about 100 lb/in^2 gauge. Damping in several of these modal configurations will be measured by observations of the free vibration.

B. Phase 2 - Bending and Longitudinal Vibrations of a Cylinder Loaded with Inert Propellant

Using the loaded cylinder previously described, the experimental procedure followed and the measurements made will be identical to those of Phase 1. A number of runs will be made, each with a different amount of propellant, some propellant will be machined away and with several values of internal pressure in order to establish how the damping and the dynamic behavior of this system change with a varying propellant mass and internal pressure.

It is realized that both Phase 1 and Phase 2 tests are behind schedule, but it is felt that the experimental technique has been sufficiently developed to permit the program to be completed on schedule.

C. Phase 3 - Propellant Mechanical Property Tests

When the analytical studies of the circular plate problem are complete, the experimental results will be applied to determine the propellant properties which can be compared with those found in the Fitzgerald apparatus tests.

Following completion of the experimental and analytical phases of the long circular grain-type problem, similar comparisons will be made.

Finally, it is hoped that a quick test can be made using the more suitable of the two above methods to determine the dynamic mechanical properties of an actual solid propellant.

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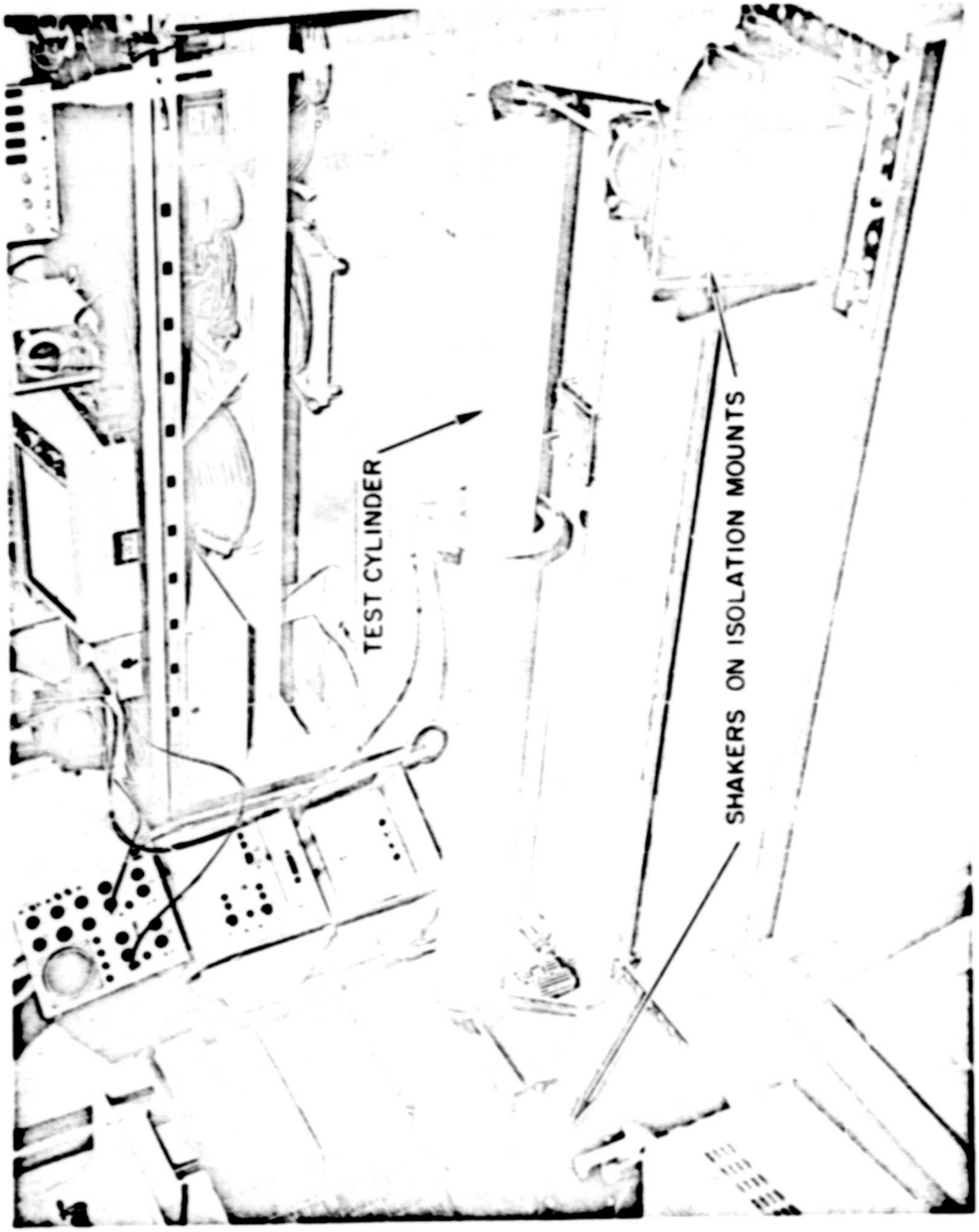

Figure 1. View of Test Cylinder and Associated Equipment.

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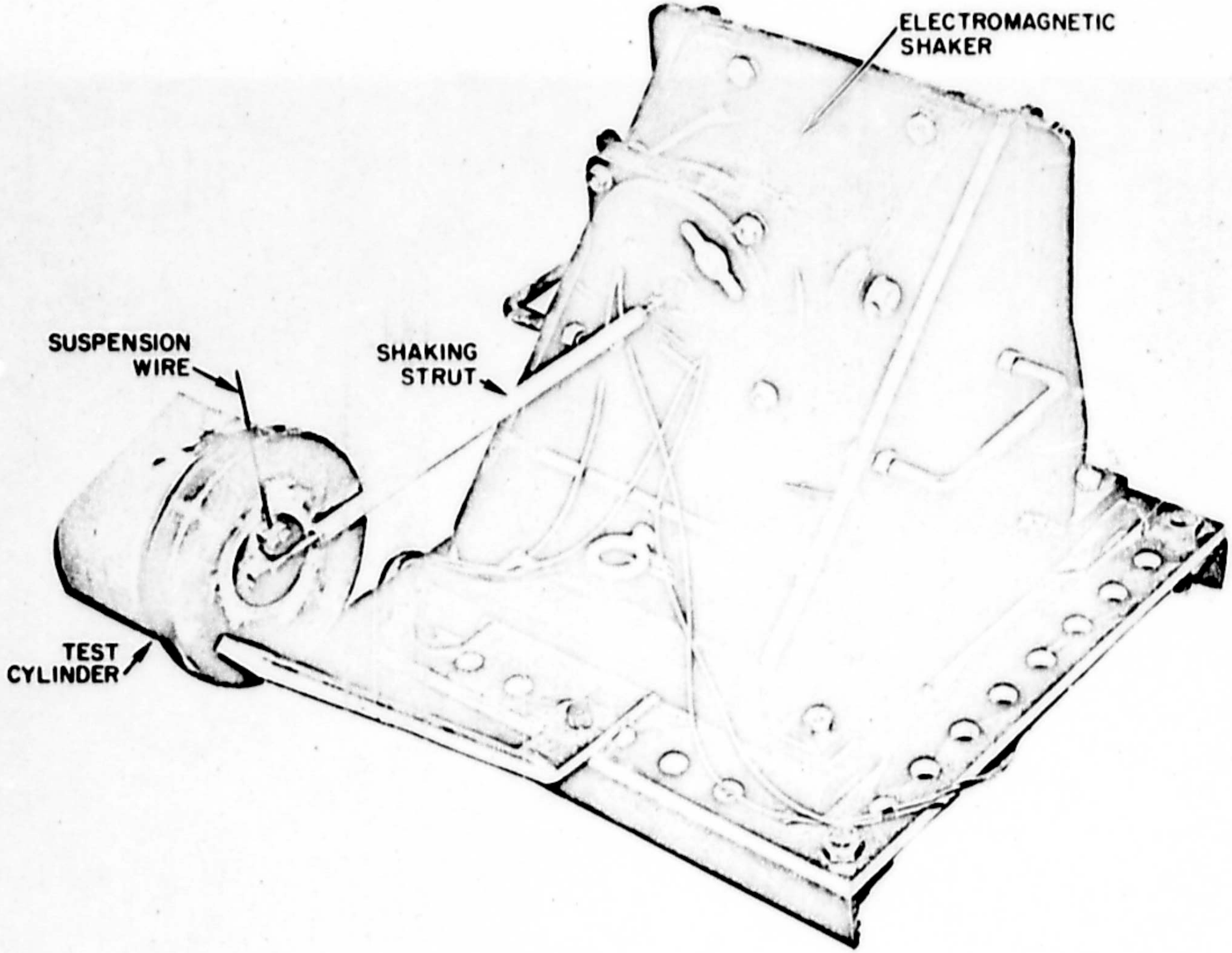

Figure 2. Details of Cylinder Suspension and Shaker Attachment.

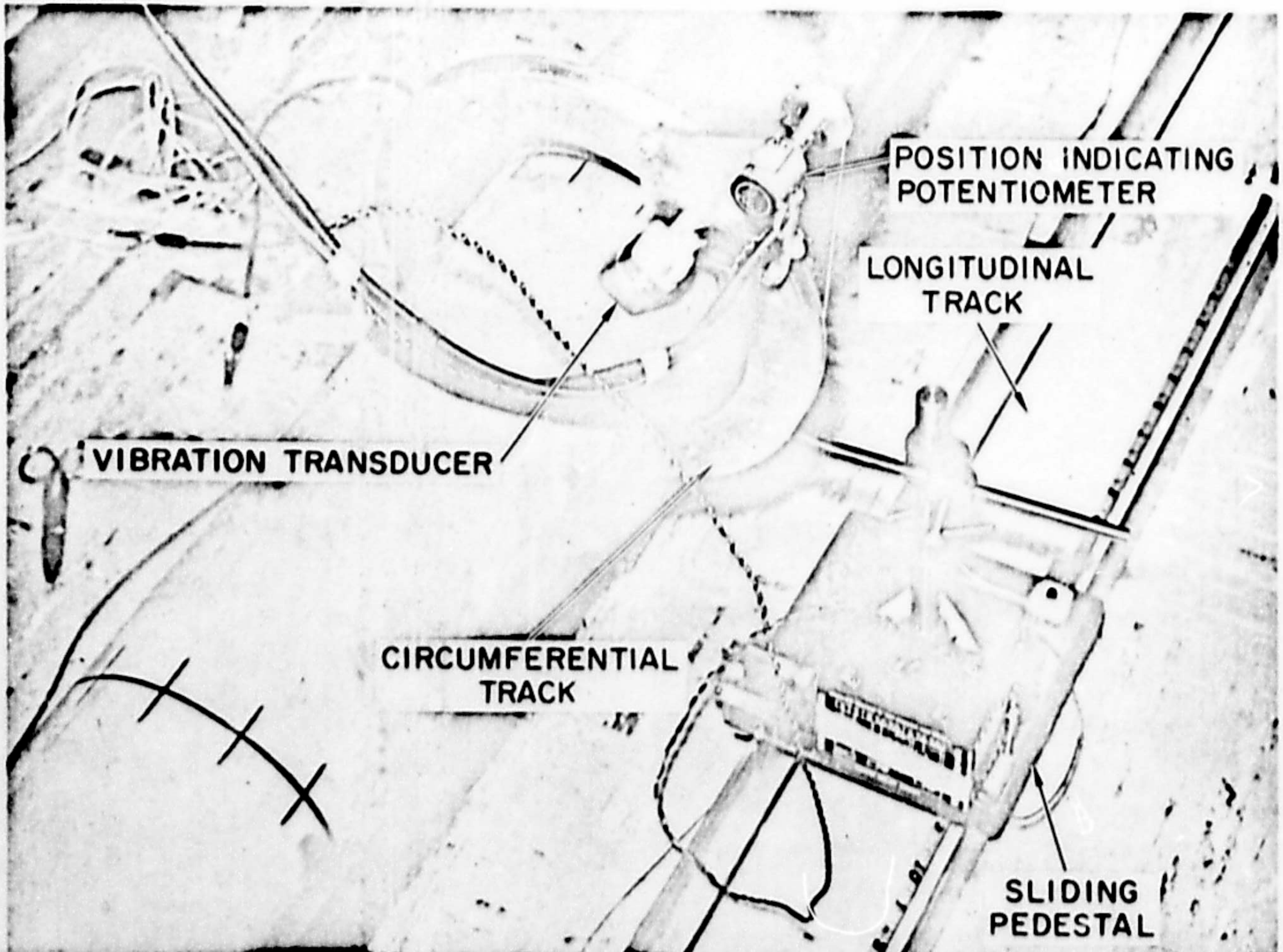

Figure 3. Details of Cylinder Scanning System.

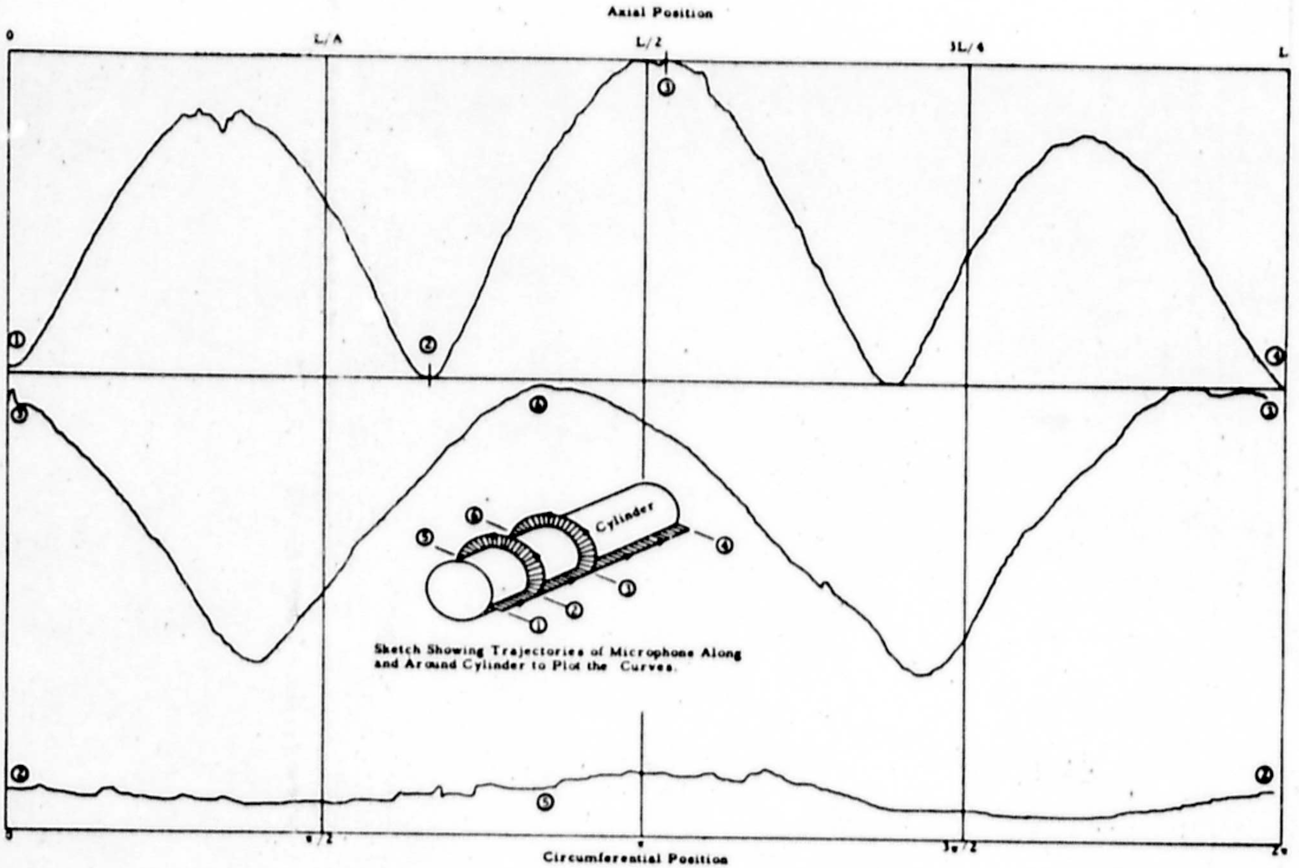

Figure 4. Typical Mode Shape Measurement Record, 617 cps.

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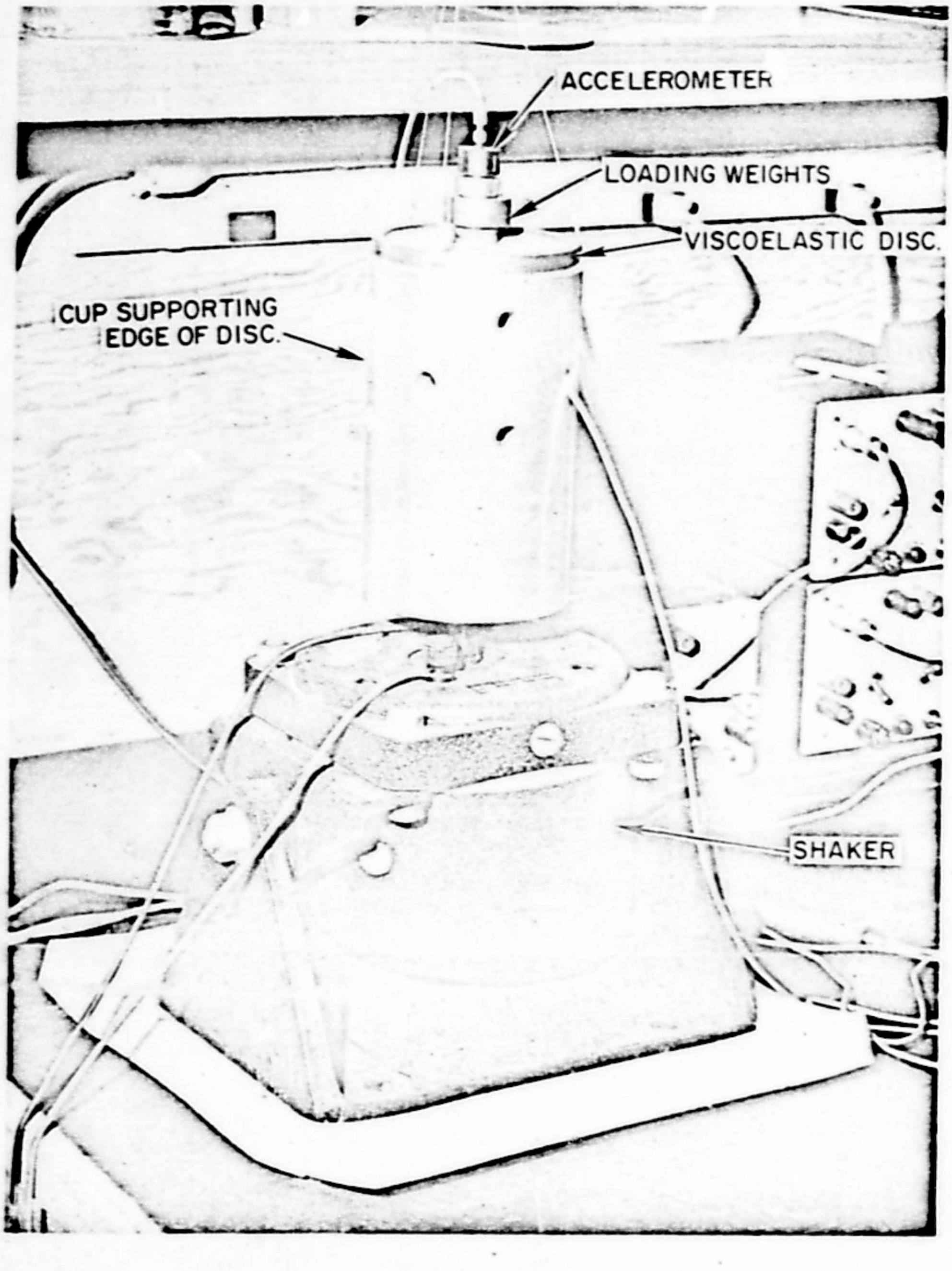

Figure 5. Circular Viscoelastic Disc Experiment.

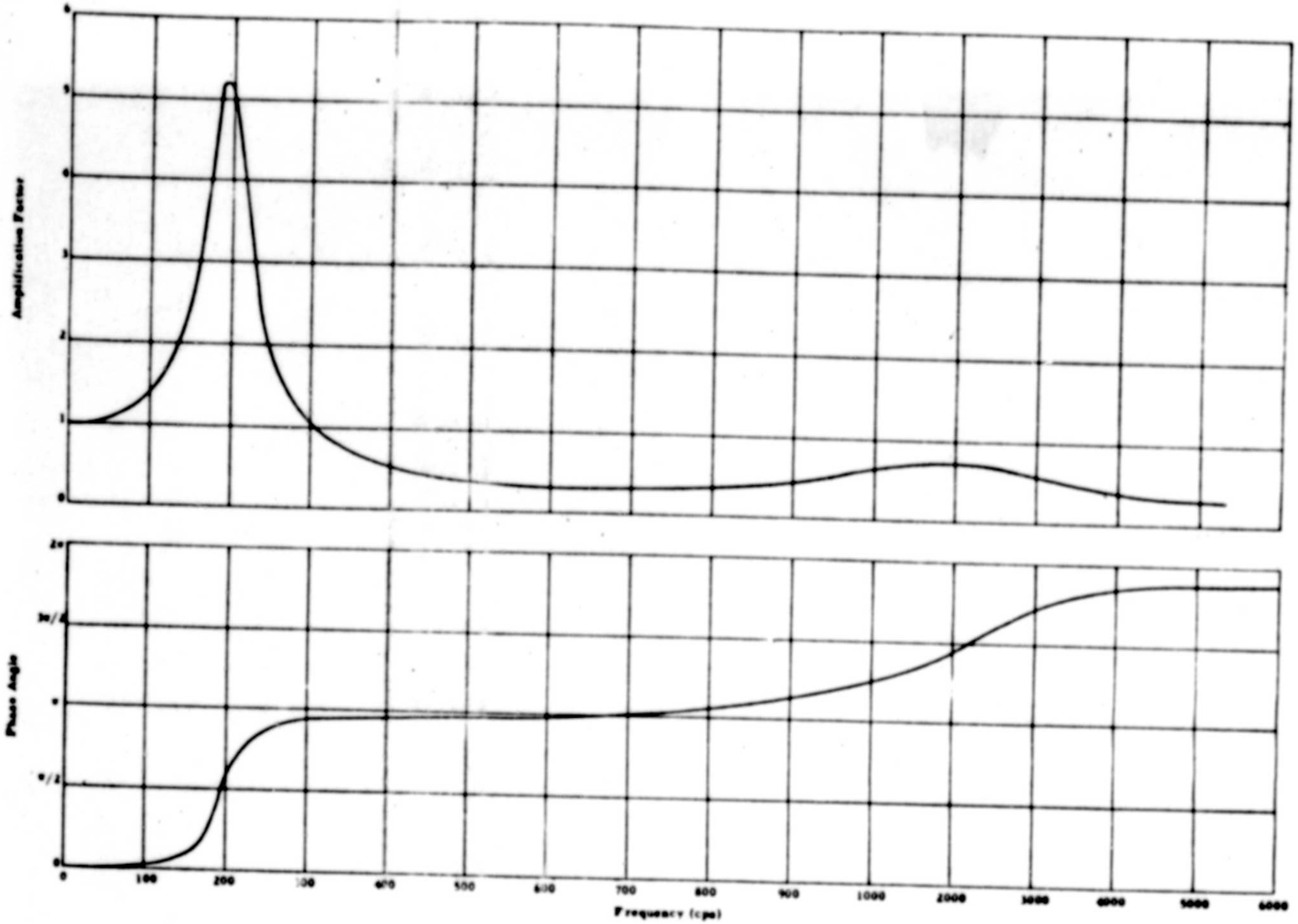

Figure 6. Graph Showing Response Characteristics of Circular Viscoelastic Disc (0.330 inch thick, 3.36-inch outside diameter, center mass = 0.068 pound).

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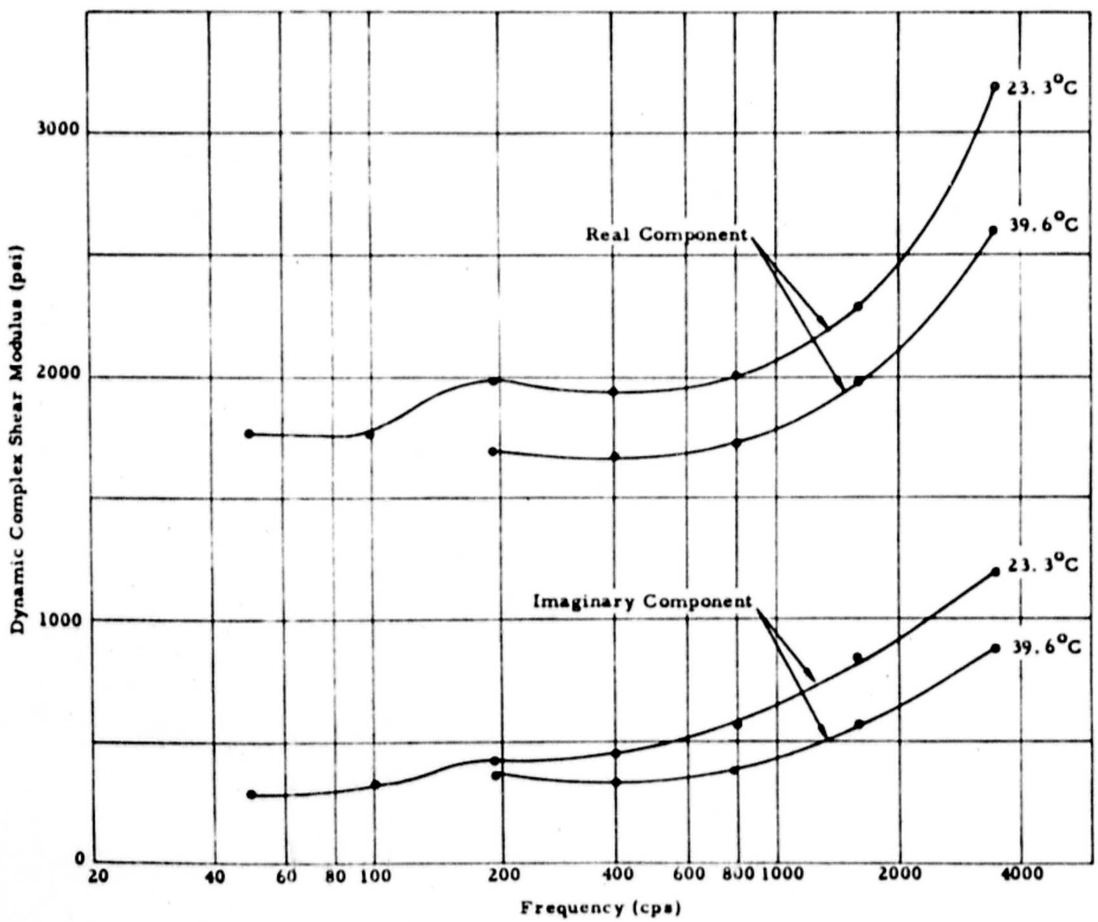

Figure 7. Results of Fitzgerald Tests for Aerojet Inert Propellant DP-16 at Two Temperatures.

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