NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-938

A Note on Boundary-Condition Simulation in the Dynamic Testing of Spacecraft Structures

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ABSTRACT

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A common practice of subjecting an entire spacecraft to a sine-sweep environmental vibration test is examined in the light of the actual boundary conditions prevailing at the interface of the spacecraft and its launch vehicle. By recourse to some simple experiments, it is shown that the conventional sine-sweep test is not only inappropriate as a structural test, but also may provide either an overly severe or an unconservative test of certain subassemblies or assemblies. Recommendations are made for fuller utilization of dynamic-response analyses that treat the flexible spacecraft as an integral part of the flexible space vehicle system. It is concluded that such analyses can aid the acquisition and interpretation of structural flight test data and, also, establish the nature of the required structural qualification testing.

I. INTRODUCTION

It has been a practice at JPL, as well as elsewhere, to conduct vibration tests of a complete spacecraft in accordance with an Environmental Vibration Test Specification that includes requirements for sinusoidal-sweep excitation, or, as it is commonly called, "sine-sweep" excitation. That is, such excitation is usually stated to be applied at the base of the test article as a constant vector (or rms, or peak-to-peak) acceleration along specified axes and over a stipulated frequency range with a prescribed time rate of frequency sweep. Commonly, the sweep rate is sufficiently low to permit essentially full development of spacecraft steady-state resonances. A typical sine-sweep specification is depicted in Fig. 1.

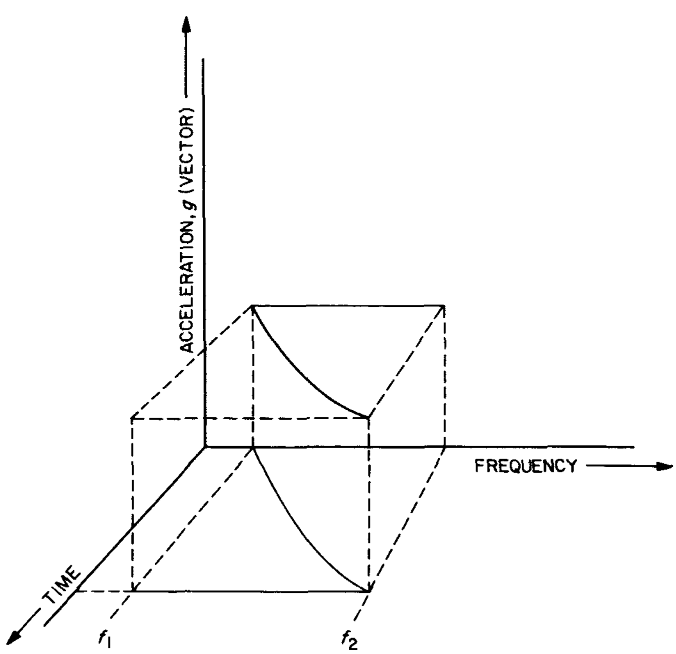


Fig. 1. A graphical representation of a typical, sine-sweep vibration test specification applying, as constant vector-acceleration, over a stipulated frequency range

Precedent for the sine-sweep vibration test has existed since some early MIL Specs were conceived, during the evolution of piston-engined aircraft, to promote the development and production of aircraft components and accessories capable of surviving operational environments. The success of this testing practice is widely recognized in the development of mechanical reliability in electronics packages and electromechanical devices for space vehicles. Perhaps less widely recognized, however, is the fundamental inapplicability of the "black-box" type of vibration test specification to a "structure." A question that has needed asking and that deserves a well-considered answer is whether a complete spacecraft should be tested as a *black box* or as a *structure*.

This report deals primarily with one aspect of the dynamic testing of spacecraft structures for design conditions derived for the launch and exit phase. First, in the terminology of structural dynamics, the aspect of "boundary conditions" existing at the interface of a spacecraft and its launch vehicle will be examined through recourse to some simple experiments. Then, since the cart will have been put before the horse by discussing *testing* before *design criteria*, the theme will be realigned to endorse, for new programs, an orderly course of dynamic analysis that treats the flexible spacecraft as an integral part of a flexible space vehicle. The dynamic analyses will derive the design loads for spacecraft structures, and, therefrom, will permit meaningful specification of the details of the spacecraft structural qualification tests.

Finally, comments are made on the general nature of structural qualification tests as related to near-term and long-range facilities planning.

II. SOME SIMPLE EXPERIMENTS AND THEIR RESULTS

For the purpose of illustration, assume that a particular space vehicle—one of a family of nominally identical vehicles—has transmitted vibration data through continuous telemetry channels during the entire launch and exit phase. Further, assume that the telemetered data from an isolated accelerometer located at the spacecraft separation plane have revealed, at a particular flight time, a transient lateral response with a dominant frequency of, say, 37 cps. The subsequent synthesis of a conventional, low-frequency, sine-sweep vibration test specification applying at the spacecraft separation plane would, in some manner, account for the observed 37-cps response as well as other observed responses within a transverse-acceleration frequency band, f_1 to f_2, such as shown in Fig. 1.

With the preceding synthesis in mind, some simple experiments have been devised with two objectives:

1. To suggest the structural consequences of constructing a black-box-like vibration test specification from flight data in the absence of a prior definition of the modal vibration characteristics of the space vehicle (launch vehicle plus spacecraft)
2. To demonstrate the importance of recognizing in-flight spacecraft/launch vehicle *boundary conditions* in specifying spacecraft structural-design loads and structural-test criteria

A structural idealization of a space vehicle that consists of a launch vehicle and a spacecraft is shown in Fig. 2. An idealization of a nose fairing over the spacecraft has been deleted because its inclusion would contribute little to the points to be made by the experiments.

Figure 3 shows a test setup for the excitation and measurement of several natural bending modes of the essentially unconstrained space vehicle. The measured mode shapes and frequencies of the space vehicle in its 2nd, 3rd and 4th bending modes are shown in Fig. 4. The mode shapes, normalized to the same reference amplitude at the nose station, show separation-plane lateral displacements in relation to the separation-plane rotations associated with the local slopes of the elastically-deformed system. Figure 5 indicates a long-used concept for defining "subsystem" (e.g., spacecraft) base motion by use of the effective center of rotation.

It can be proved from purely theoretical considerations that if, in the test laboratory, the base of the spacecraft is given the same translational and rotational motions that it experiences in flight, then the time histories of stress distributions and elastic deformations will also be the same as those experienced in flight. However, since an experimental demonstration provides a physical picture that is more easily understood than a formal mathematical proof, a "tuned, rocking shake table" was

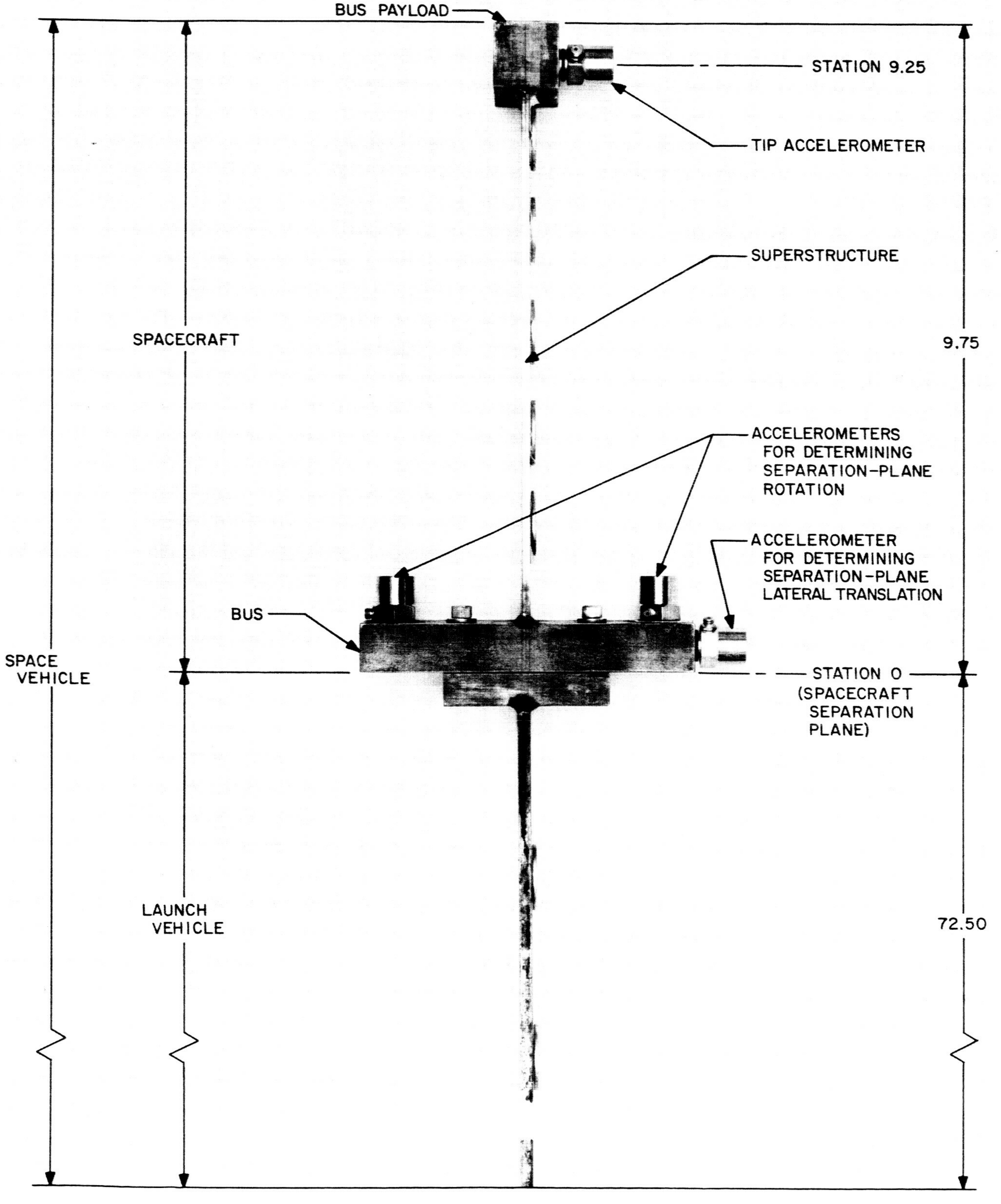


Fig. 2. Structural idealization of a laterally-flexible space vehicle

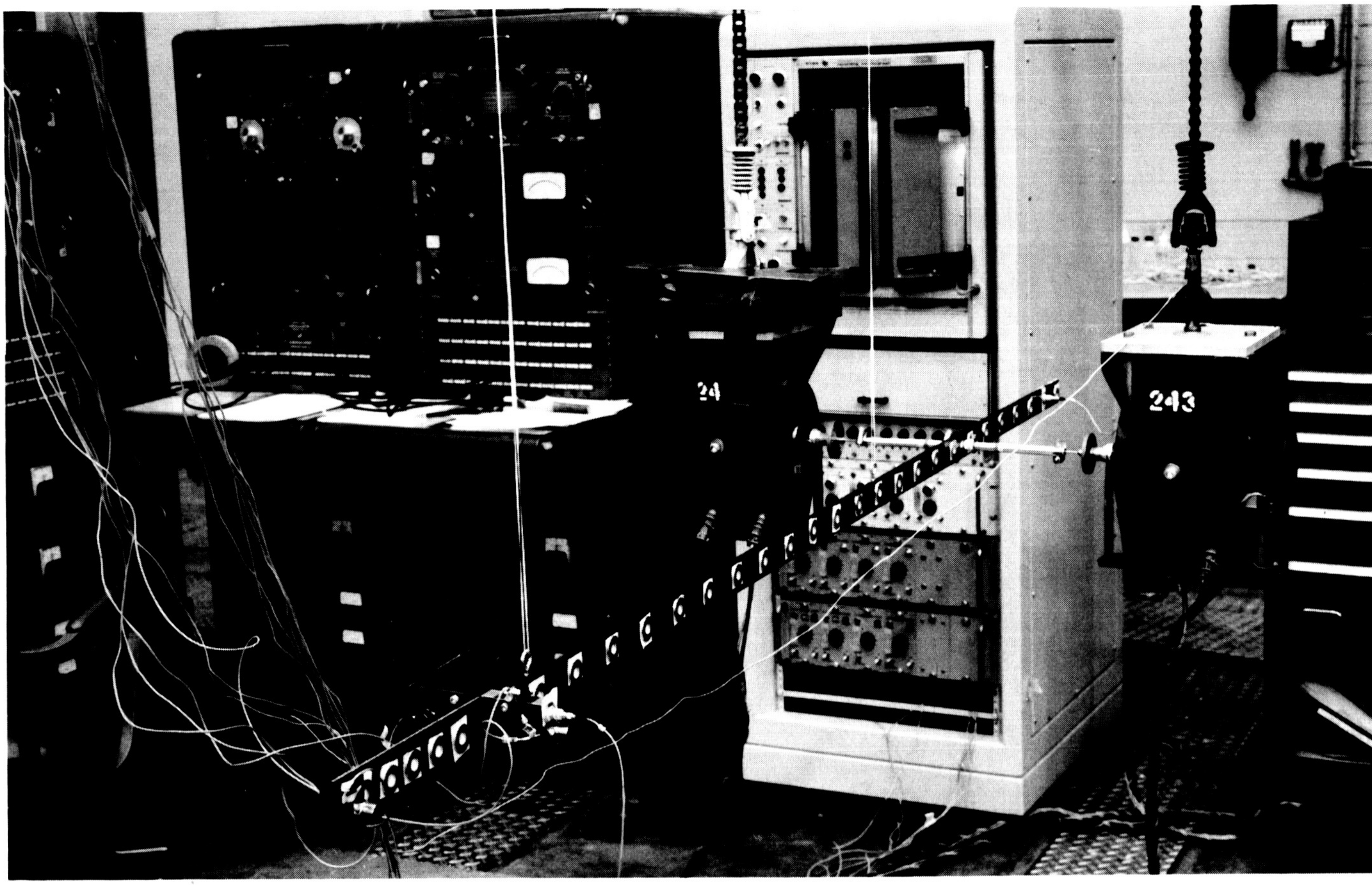


Fig. 3. Test setup for exciting free-free bending modes of space vehicle

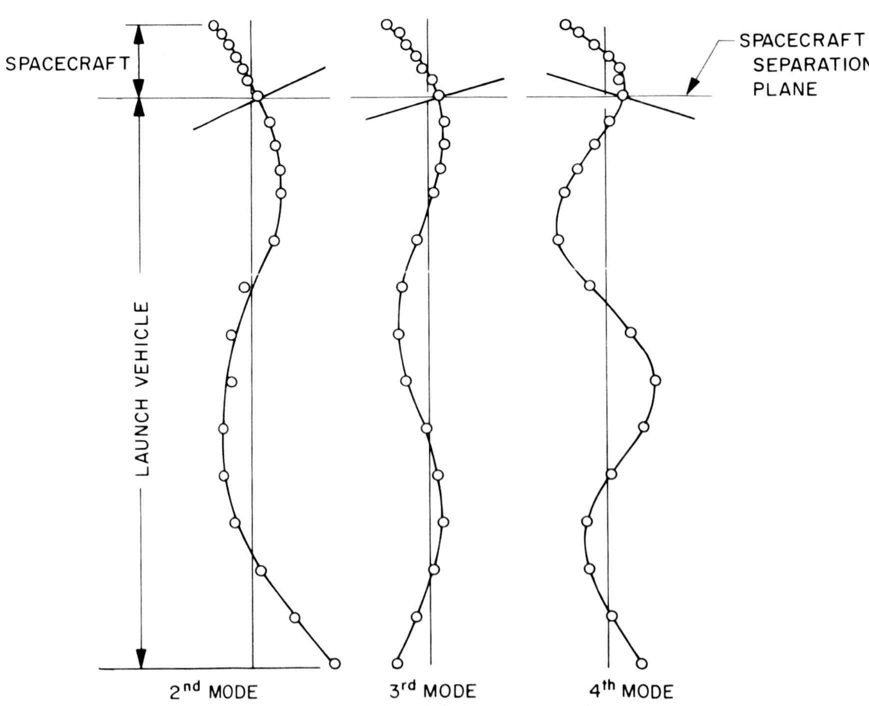


Fig. 4. Several free-free bending modes of space vehicle

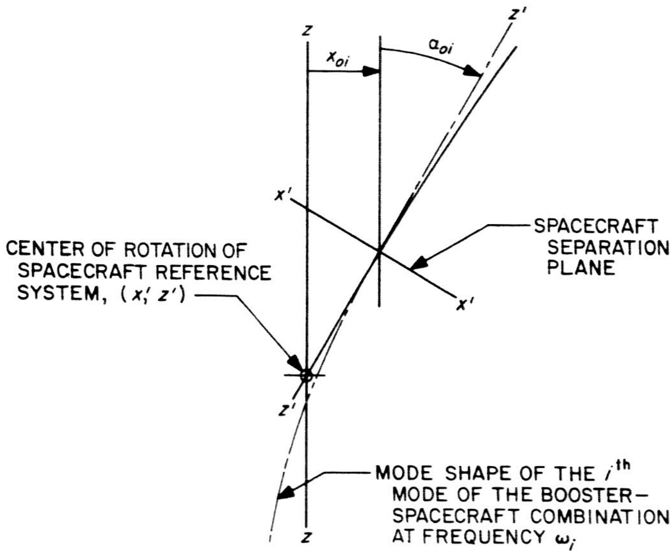


Fig. 5. Representation of spacecraft separation-plane modal response by motion about an effective center of rotation

designed and constructed for performing laboratory tests of the spacecraft; this device (Fig. 6) has a translation table that is supported on a base fixture by flexure plates at each end. A rotation table is attached to the translation table by a single-axis flexure pivot. In this particular mechanization, a link between the rotation table and the base fixture may be adjusted to place the effective center of rotation at any desired distance above or below the test-table surface.

The natural vibration modes of this system can be considered as linear combinations of rigid-body translation, rigid-body rotation, and cantilever modes of the test specimen. By the selection of flexure stiffnesses and by the use of mass ballast, the characteristics of one of the natural modes of the test system may be made to give test-table motions that duplicate the translational

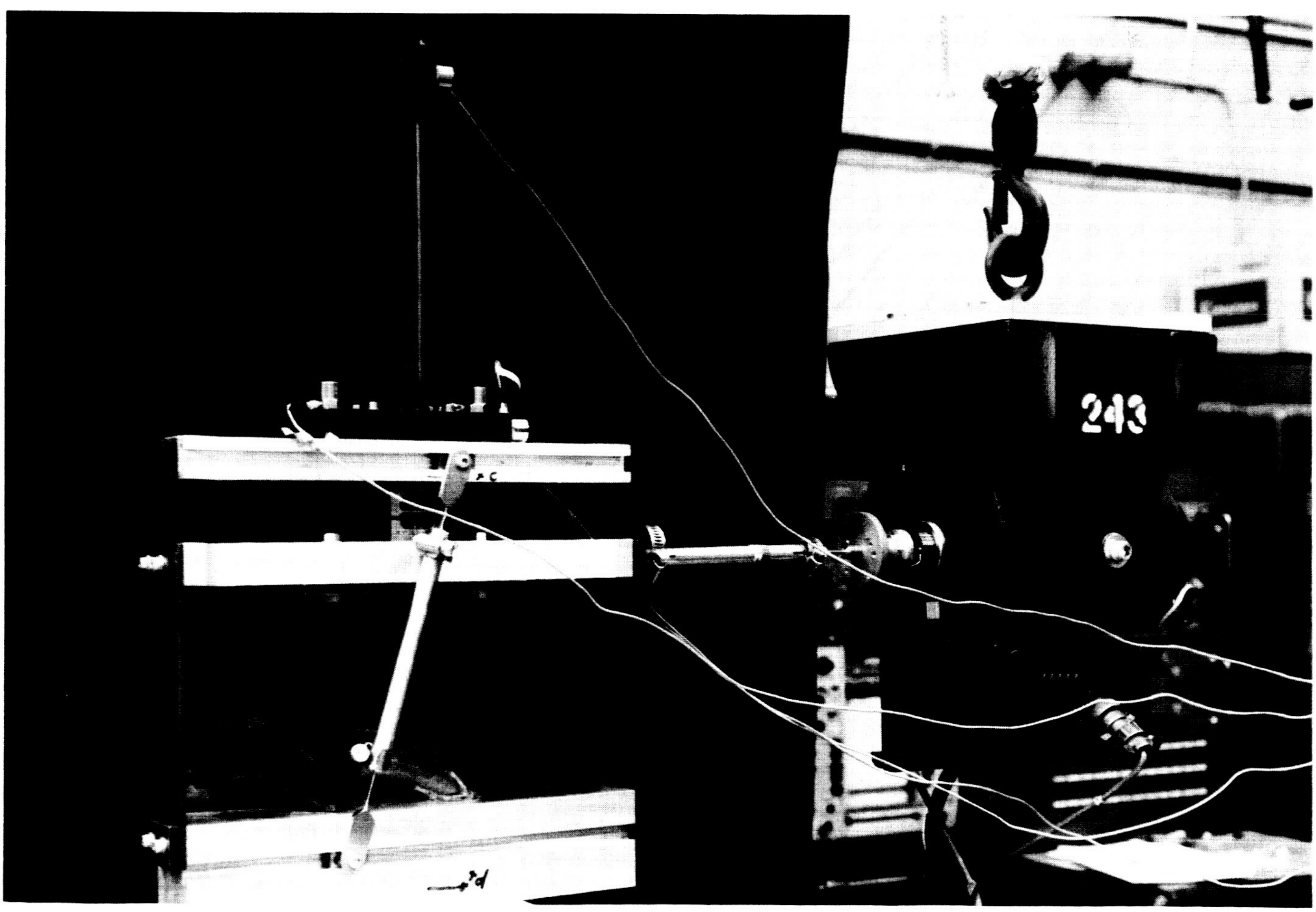


Fig. 6. Spacecraft mounted on tuned, rocking shake table

and rotational motions of the base of the spacecraft in any one of the normal bending modes of the launch vehicle/spacecraft combination.

The rudimentary device of Fig. 6 was mechanically adjusted to give a close approximation of the frequency and the effective center of rotation of the spacecraft separation plane in the 4^{th} bending mode of the space vehicle (Fig. 4). Excitation of the test system was effected by a small shaker directly driving the translation table.

Figure 7a shows the simulated spacecraft oscillating as an integral part of the complete space vehicle in its 4^{th} bending mode. Figure 7b shows the spacecraft oscillating on the tuned, rocking shake table (note the similarity of the amplitude distributions).

To complete the demonstration, the flexure pivot was removed from the test device, and the rotation table was clamped to the translation table. In this test-system configuration, a conventional sine-sweep test was performed with a constant rms acceleration input. At a frequency of 24.7 cps, the first cantilever bending mode of the spacecraft was excited. The system response during the first cantilever bending mode excitation is shown in Fig. 8. The differences in spacecraft motions between those in Fig. 8 and those in Figs. 7a and 7b are quite marked, notably at the separation plane and at the middle of the "superstructure."

The shaker force producing the deflections shown in Fig. 8 was purposely adjusted so that the *tip amplitude* was roughly comparable with the tip amplitudes shown in Figs. 7a and 7b. Had it been attempted to match the *separation plane* lateral acceleration with those of Figs. 7a and 7b, either of two events would have transpired:

1. The small (25-lb vector force) shaker would have had insufficient exciting force and the tests, as specified, could not have been carried out.

2. The spacecraft would have experienced structural failure *at the point of minimum acceleration—not at the point of maximum acceleration.* The point of minimum acceleration, in this example, is the point of maximum shear and bending stresses, located at the juncture of the superstructure and the bus of Fig. 2.

Either of these eventualities contains the essence of the differences to be expected when structural criteria are defined by a *black-box* type of environmental vibration specification rather than by motional inputs that satisfy the proper boundary conditions. A more quantitative examination of this situation illustrates the structural inadequacies of the sine-sweep test and the need for a more comprehensive approach to the specification of spacecraft structural design and test criteria. Figure 9 presents plots of spacecraft measured acceleration distributions in the three cases sequentially discussed in the following paragraphs:

Case 1: Flight. The spacecraft is oscillating as an integral part of the complete space vehicle in its 4^{th} bending mode at 37.3 cps (see Fig. 4).

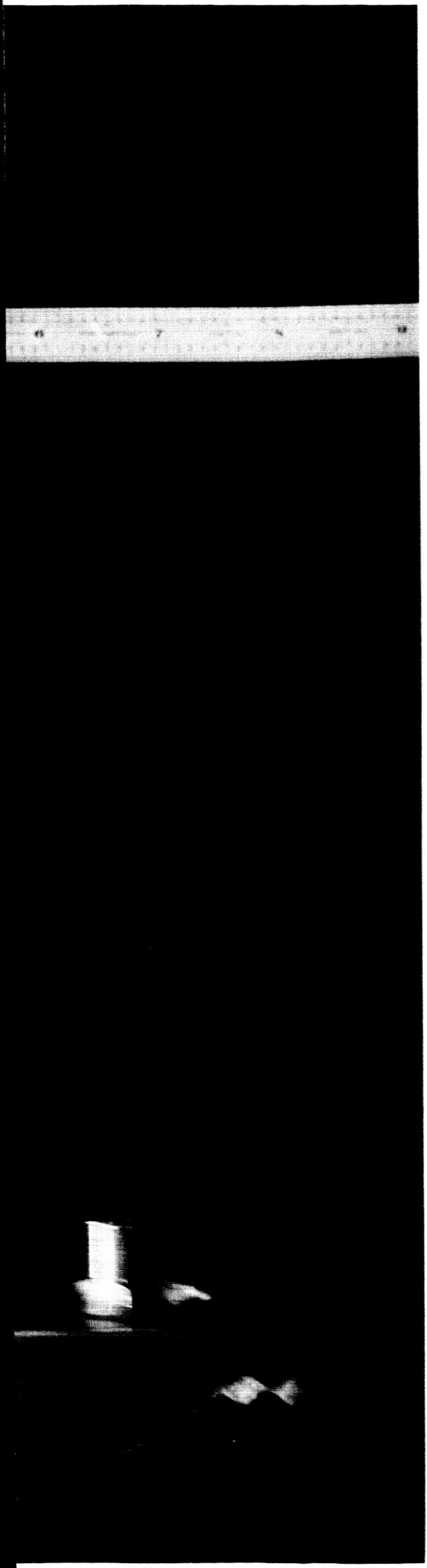
Case 2: Flight-Simulation Test. The spacecraft is oscillating at 37.3 cps on a tuned, rocking shake table with the table input motion matched to the separation plane motion in Case 1. (In Fig. 9, the solid circles for Case 2 represent the results of table adjustments to match the outputs of the three base accelerometers designated by squares for Case 1.)

Case 3: Conventional Sine-Sweep Test. The spacecraft is oscillating in its approximate[1] first cantilever bending mode at 24.7 cps. (In Fig. 9, the Case 3 acceleration distribution is arbitrarily renormalized to match the tip-acceleration reading of Case 2.)

In support of the design and test of such items as electronic packages, mounting bracketry, etc., concern with local acceleration is required. In contrast, to support the development of the basic structural configuration, and the detailed design and test of the structural hardware, application of technology in structural dynamics is concerned less with local accelerations, per se, than with the associated inertia-load distributions. For the simple spacecraft idealization shown in Fig. 2, it is sufficient to perform two successive integrations of the inertia-load distribution to obtain the classical "shear" and "bending-moment" diagrams. Figure 10 presents shear and bending-moment diagrams for Cases 2 and 3 as depicted in Fig. 9. The fact that the Case 3 separation-plane shear is about twice that of Case 2—and in the improper direction at that—may appear to be a mere technical detail in recognition of the arbitrariness of the renormalization of the Case 3 acceleration distribution (Fig. 9).

[1]Unwanted rotational flexibility of the translational table is shown by the measured separation-plane orientation. Results of spacecraft modal surveys with a much more rigid base support are shown in Fig. 13.

Fig. 7a. Spacecraft motion in 4th bendi
of space vehicle, Case 1



mode

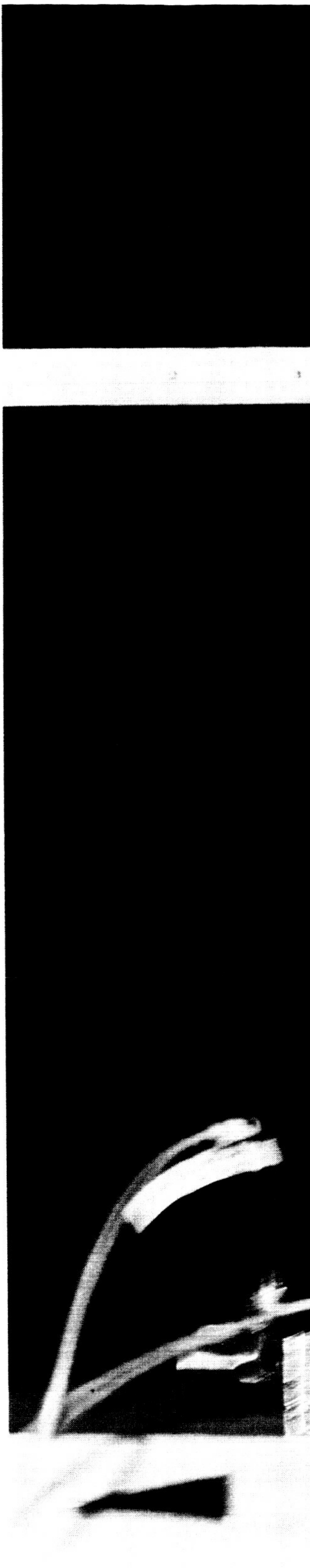


Fig. 7b. Spacecraft m

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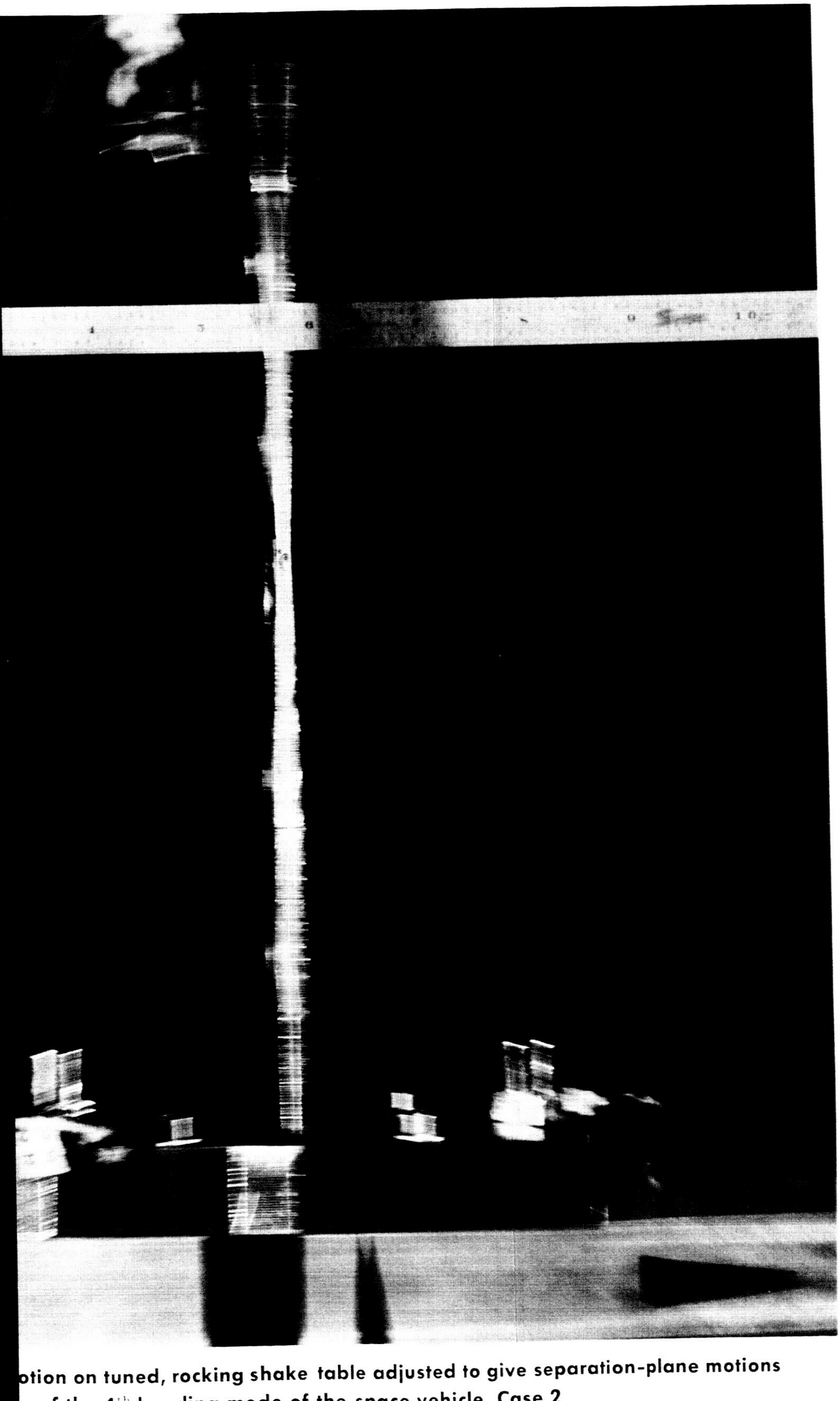
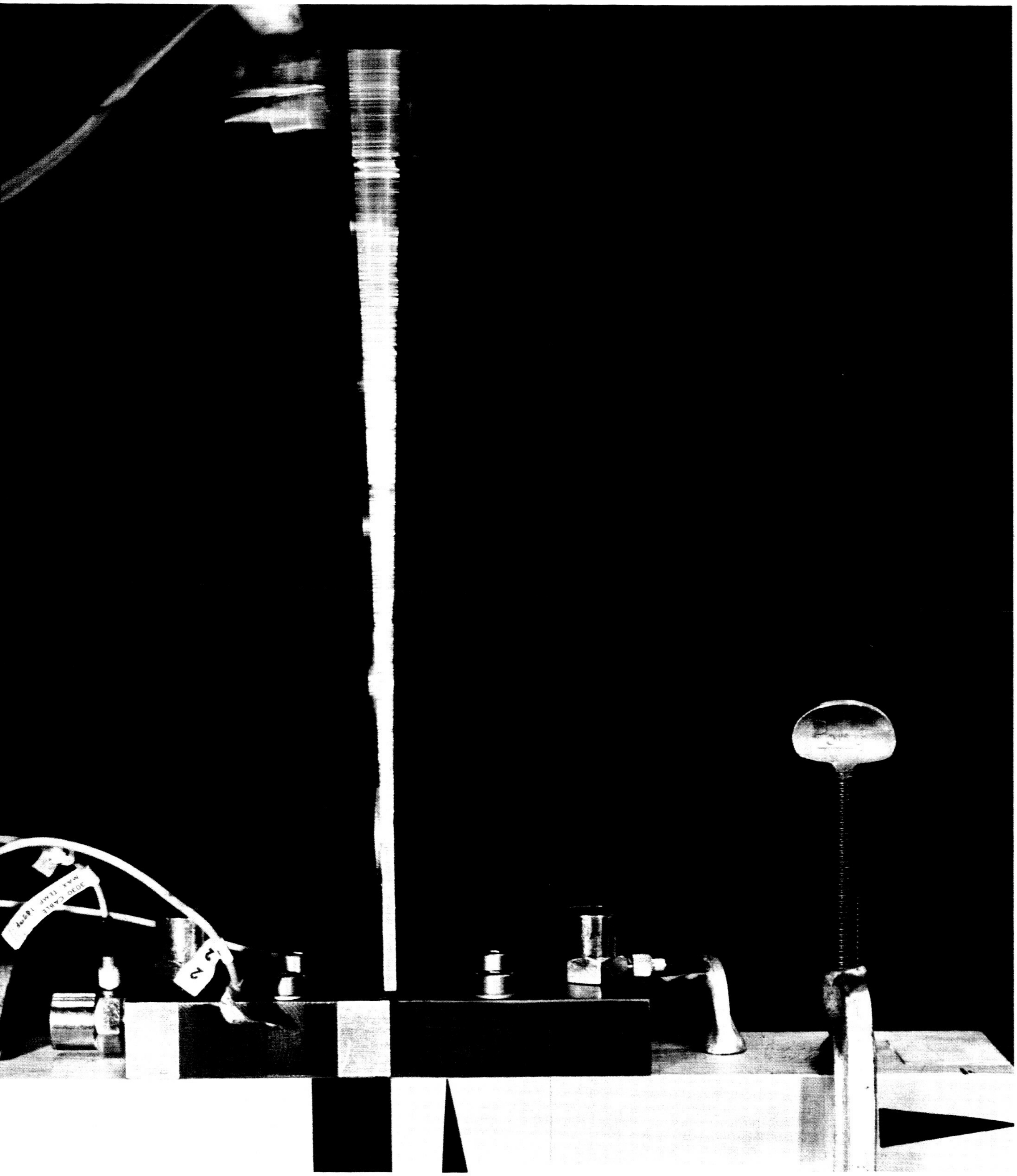


otion on tuned, rocking shake table adjusted to give separation-plane motions of the 4th bending mode of the space vehicle, Case 2



3. Spacecraft vibrating in its 1st cantilever bending mode during a conventional low-frequency, sine-sweep test, Case 3

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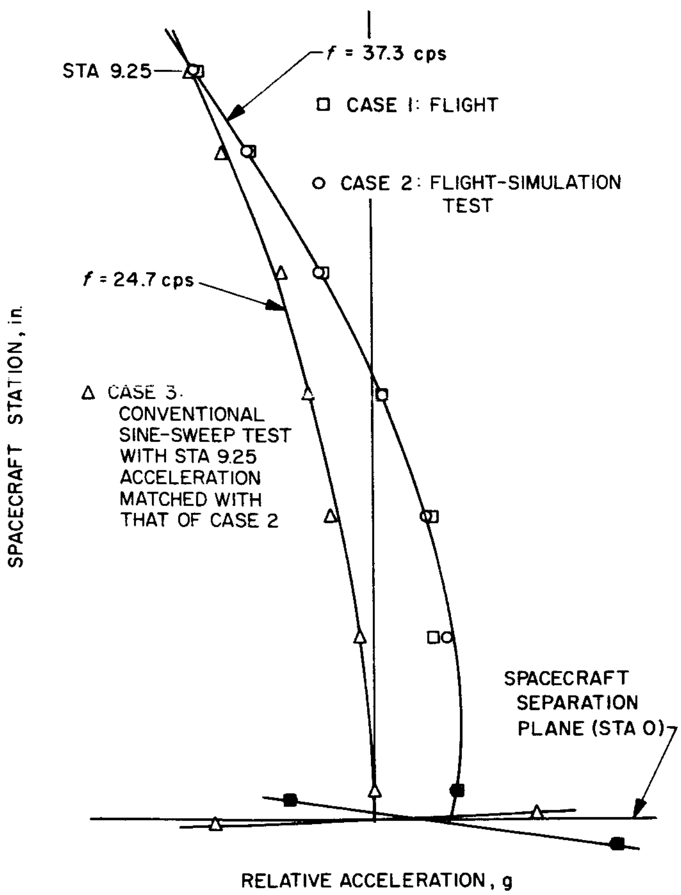

Fig. 9. Spacecraft acceleration distributions in flight and in shake-table tests

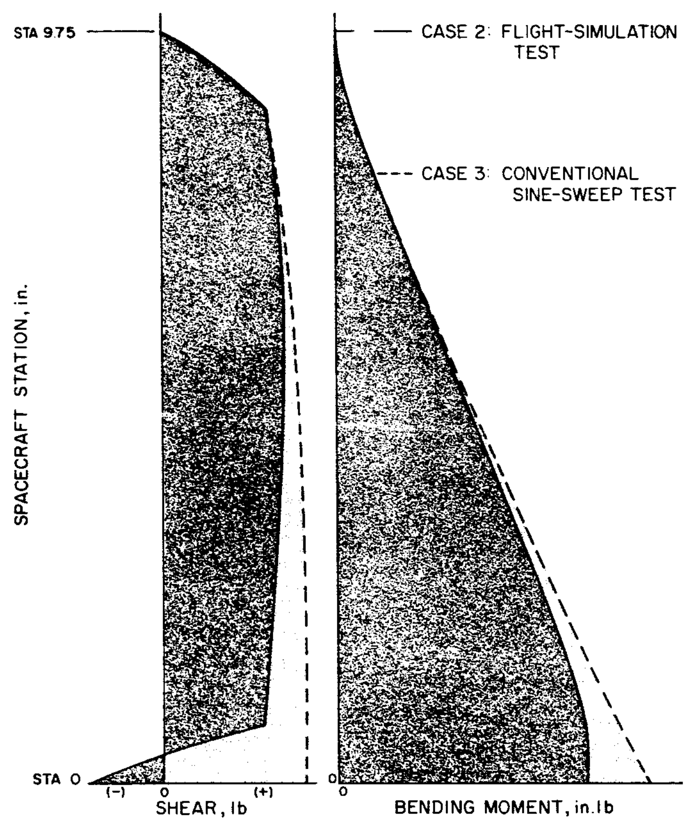

Fig. 10. Spacecraft shear and bending-moment distributions in shake-table tests with lateral accelerations matched at sta 9.25

It was assumed, at the beginning of this section, that a vibration test specification similar to that of Fig. 1 was synthesized from telemetered flight data to apply at the *separation plane*, and not at the forward extremity of the spacecraft. Accordingly, the comparison of acceleration distributions should be as represented in Fig. 11. The shear and moment diagrams corresponding to Fig. 11 are shown in Fig. 12.

In Fig. 11 the tip acceleration for Case 3 is slightly over 50 times the Case 2 tip acceleration. Since, at constant acceleration, amplitude varies inversely as the square of the frequency, the dynamic displacement distribution in Case 3 is more than 100 times that in Case 2.

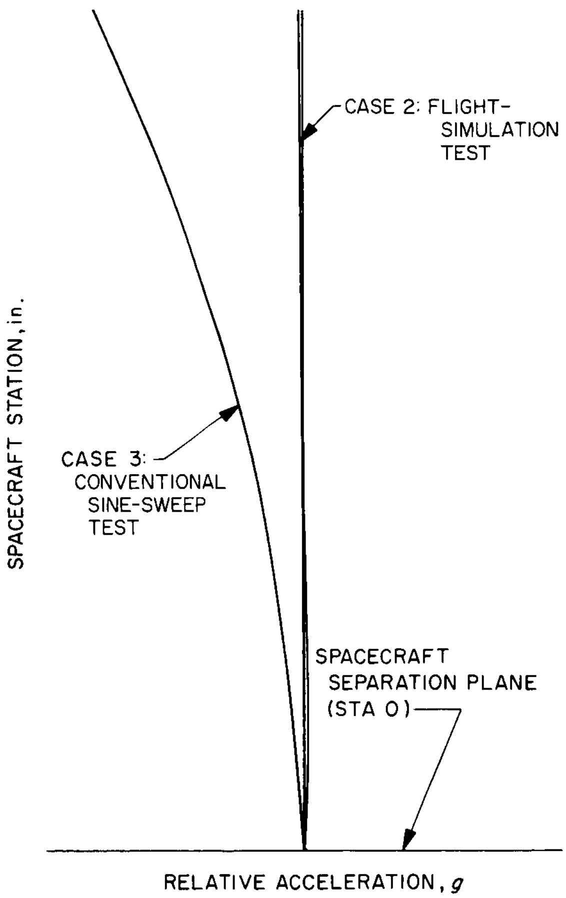

Fig. 11. Spacecraft acceleration distributions in shake-table tests with lateral accelerations matched at separation plane

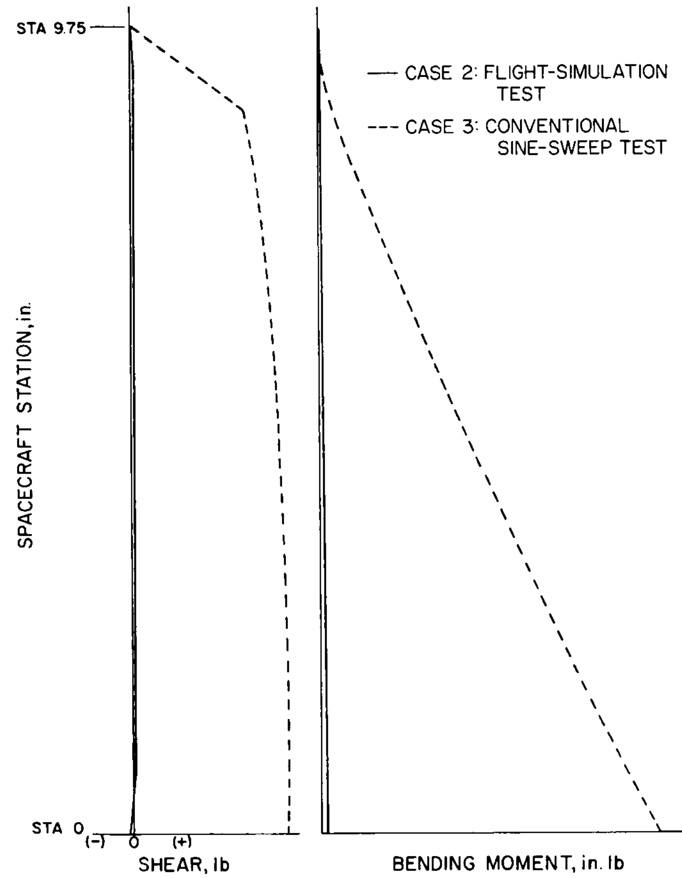

Fig. 12. Spacecraft shear and bending-moment distributions in shake-table tests with lateral accelerations matched at separation plane

III. SOME COMMENTS RELATING TO THE EXPERIMENTS

At the outset of the experimental program described herein, it was not anticipated that the Case 2 and Case 3 comparisons (leading, subsequently, to Figs. 11 and 12) would exhibit such drastic differences. One important reason for the magnitudes of these differences is associated with the low structural damping (or high Q) of the welded spacecraft. However, it is equally important to note that the objectives of the Case 3 and Case 2 tests were quite different. In Case 3, the adoption of a continuous frequency sweep committed the spacecraft to resonate in any cantilever mode within the frequency band. In contrast, the Case 2 test was performed to match the spacecraft/launch vehicle boundary conditions that would prevail during in-flight oscillation in a single bending mode of the system.

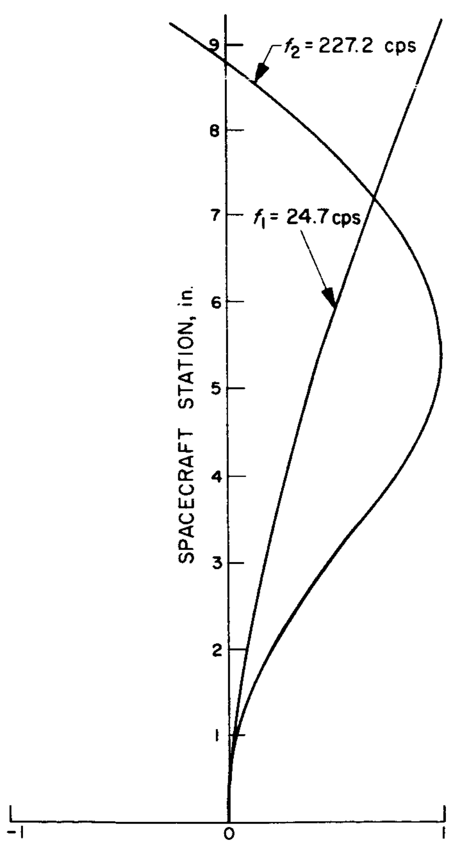

Fig. 13. First two cantilever bending modes of spacecraft, mode shapes normalized to unity at station of maximum deflection

Whereas the tip accelerations and root bending moments of the Conventional Sine-Sweep Test and the Flight-Simulation Test are approximately in the ratio of 50 to 1, if the same type of experiment had been made using the 3rd instead of the 4th bending mode of Fig. 4, the ratio would have been more nearly 30 to 1. Similarly, with a choice of the 2nd bending mode, the ratio would have been only about 17 to 1. Then, again, if a different structural idealization had been chosen for the space vehicle, it would not be possible without either test or dynamic analysis to predict how the comparisons would appear.

Thus, the intent of these illustrations has not been to produce a particularly bizarre numerical contrast, but to show one way in which the conventional sine-sweep test violates the physics of the in-flight situation.

There are some concluding observations to be made. Figure 13 presents the results of modal vibration surveys of the spacecraft first and second cantilever modes with a more rigid base support than was obtainable with the sprung shake table. The frequency of the first mode, at 24.7 cps, was unchanged. The frequency of the second mode was established at 227.2 cps. Modal damping coefficients were established from the logarithmic decrement of the oscillation decays resulting from abrupt removal of exciter force. From the known mass distribution, measured mode shapes, frequencies, and damping coefficients, the amplitude ratio of "bus-payload" acceleration to separation-plane acceleration has been calculated over a wider frequency range than that over which the sine-sweep tests were performed. The results of these calculations (Fig. 14) are in reasonably good agreement with the measured amplitude ratio at a frequency of 24.7 cps.

Figure 14 also shows discrete amplitude ratios corresponding to the frequencies and mode shapes of the space vehicle 2nd, 3rd, and 4th bending modes of Fig. 4. Whereas the amplitude ratio of the conventional sine-sweep test is higher by a factor of about two at the 3rd bending mode, it is lower at the frequencies of the 2nd and 4th bending modes by factors of four and two, respectively. This is merely to say that the continuous curve of Fig. 14 may be regarded as the *available* amplitude ratio in the conventional test, and the solid circles give the amplitude ratios *required*, by virtue of mode shapes, at the specific frequencies of the discrete bending modes. Thus, the conventional sine-sweep test of a complete spacecraft is neither appropriate for a structure, nor is it necessarily a *conservative* test of the black boxes.

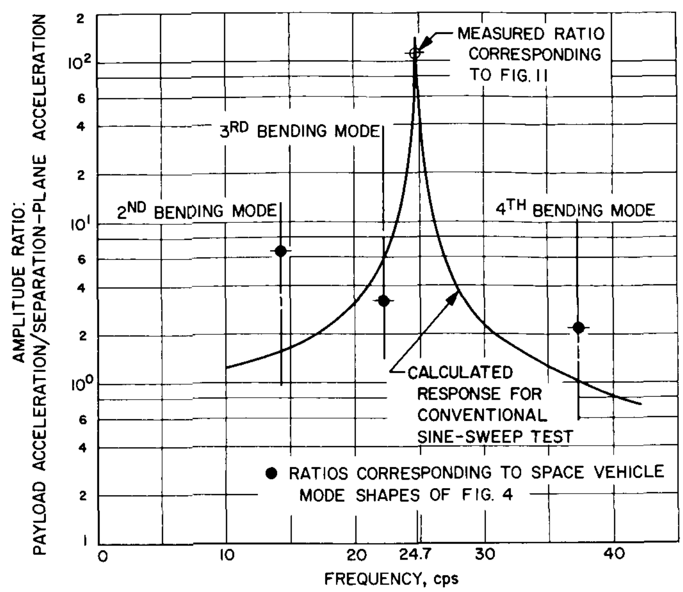

Fig. 14. Graph showing unconservatism of the conventional sine-sweep test for the bus payload at frequencies of the 2nd and 4th bending modes of the space vehicle

IV. A REALIGNMENT OF PERSPECTIVE

Although structural qualification testing has been discussed *before* structural design loads, it is contended that design loads for a new configuration should be determined by the best available techniques, and that the nature of the required structural testing should follow, rather than precede, the loads determinations.

There are two general approaches to the establishment of critical design loads. The traditional and probably the more reliable approach is that of structural-dynamics analysis supported by whatever ground testing that may be required to promote the desired confidence level. The other approach, the *empirical* one, seeks to derive meaningful spacecraft "inputs" from space-vehicle responses measured in flight.

The experiments described in this report point out a major pitfall in reliance solely on flight data from an all too limited number of measurement locations. It is a fact that there never have been (and probably never will be) enough channels of continuous telemetry allocated to accelerometers or strain gages to define, in requisite detail, the structural response of a complex spacecraft during boost. On the other hand, a knowledge of the structurally important normal vibration modes of the complete space vehicle can contribute significantly to a good choice of in-flight sensor locations, and to the meaningful interpretation of whatever flight test data can be made available. As one example, during the flights of the *Ranger Block III* vehicles, tangentially-oriented accelerometers were placed in the adapter section, a few inches below the spacecraft separation plane, to define the character of the torsional-acceleration transient occurring during *Atlas* booster engine cutoff (BECO). From modal vibration surveys of a *Ranger* spacecraft mounted on an adapter section, it was established that, at the 67 cps frequency of the dominant pulse component, the flight accelerometers *saw* only about one-fifth of the torsional response that the spacecraft attachment points experienced (Refs. 1 and 2).

There are logical explanations for the adoption of the empirical approach. For one thing, the early satellites did look more like black boxes than structures. For another, there are some tangible advantages to program management in simplifying the contractual interfaces between a spacecraft and its launch vehicle. The conventional environmental vibration test specification, when applied to the spacecraft, appears to contribute to this simplification.

Within the last few years, JPL has been studying the problems of technical management associated with the performance of formal dynamic-loads analyses of complete space vehicles, the separate stages of which are commonly under development by different industrial contractors, with contractor direction commonly administered by different organizational segments of NASA. One of the basic problems is clearly that of uniformity and continuity in technical communication.

A customary starting point in dynamic-loads analysis is the computation of a set of normal vibration modes of the vehicle system. These modes are then used as "generalized coordinates" in response analyses for transient disturbances such as those associated with engine thrust buildup or tailoff, staging, and gust encounterment. Hurty (Ref. 3), presents one concept of modal vibration analysis that is particularly suited to the treatment of multistage space vehicles. Lang (Ref. 4), discusses concurrent work in the development of a structural analysis system, using matrix interpretive routines, which, either alone or in combination with a computer program based upon the component-mode-synthesis approach of Hurty can materially ease the mechanics of modal vibration analysis (Ref. 4).

Currently, an engineering manual is being prepared on loads criteria and related analytical techniques for flexible space vehicles during launch and exit phase.[2] The *Atlas/Centaur/Surveyor* vehicle is being used in illustrative applications of basic loads criteria and of analytical techniques for the use of these criteria. Suitable analytical models of the *Atlas* and *Centaur* stages have been provided to JPL,[2] and a mathematical model of the *Surveyor* spacecraft, derived from modal vibration surveys, has also been obtained.[3] Using an appropriate computer program, JPL has "assembled" the spacecraft on the launch vehicle in a manner that insures the matching of structural boundary conditions at the common interface. Normal vibration modes of the complete vehicle, corresponding to configurations at several flight times, have been computed with the punched-card output in a format compatible with the input of the response-analysis programs.[2] It can be mentioned that the planning and execution of this effort has been intended as a pilot run on an orderly mode of operation between the two different organizational participants.[4]

A proposal to institute the generation of spacecraft structural-design loads through a program of dynamic analysis needs consideration of qualification testing techniques. The definition of the word *simulation* (appearing in the title of this report) is taken as *reasonable approximation*, rather than *high-fidelity reproduction.* Ways to envelope critical loading conditions by use of unsophisticated test equipment merit careful examination since the cost of new engineering test facilities is a matter of concern to many.

The tuned, rocking shake table has a useful, if limited, application as a low-budget testing device. It is a common practice, in dynamic-loads analyses for certain types of transient disturbances, to *tune* the time duration of the transient to give maximum response in a particular space-vehicle mode. Serrani (Ref. 5), for example, presents the results of gust-response analyses wherein the wavelength of a discrete gust profile was successively adjusted to give maximum responses in each of the first six bending modes of the space vehicle. Figure 15 presents a computed response in the gust condition that is critical insofar as spacecraft inertia loads and spacecraft/nose-fairing clearance are concerned. The computed response is dominantly in the mode for which the gust was tuned. Accordingly, an acceptable laboratory test for this condition might employ a rocking shake table tuned to give the proper frequency and effective center of rotation in one of its several natural modes. Since the test to be performed would now be a resonance test, a relatively small electrodynamic shaker could be used in a slowly-swept *amplitude* variation at *constant frequency.*

[2]General Dynamics/Convair (under JPL contract).

[3]Hughes Aircraft Company.

[4]Results of this joint effort will appear in companion documents around mid-1966.

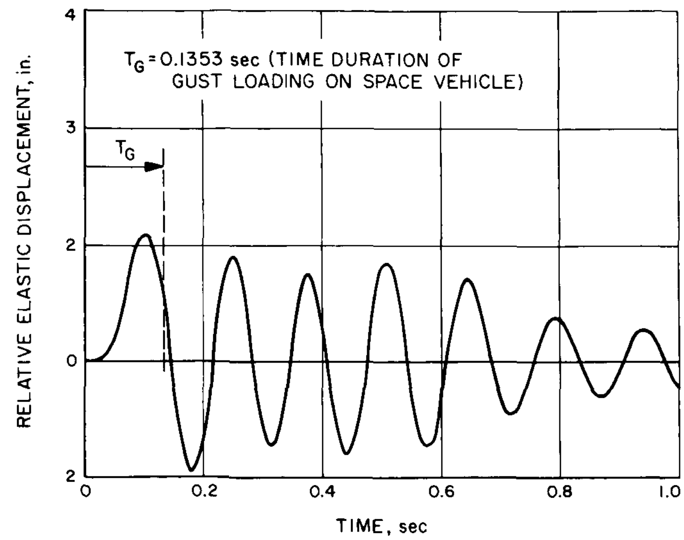

Fig. 15. Time history of relative elastic displacement of nose fairing and spacecraft extremity as derived from gust-response analysis

For critical design conditions having significant responses concurrently in several space-vehicle modes, the tuned, rocking shake table is, in general, not a suitable testing device. Here, it may be necessary to resort to *brute-force* shaking with large exciters having a preprogrammed input. The *Surveyor* torsional tests (Ref. 2) made use of a newly developed technique in which the voltage control for the electrodynamic shakers was obtained on magnetic tape from an analog computer representation of the spacecraft, the fixturing, the electromechanical characteristics of the shaker system, and the desired acceleration-time history.

Study of these and other testing concepts is continuing. All of the concepts for the dynamic testing of spacecraft structures should have one objective in common: to give a *reasonable* approximation of the critical loading conditions established by dynamic-loads analysis.

V. SUMMARY

Analytical and experimental technology in structural dynamics is sufficiently advanced that it can contribute importantly to the *development* and to the *application* of rational design and test criteria for a spacecraft in its launch and exit phase. The experiments described herein suggest that the adoption, for whatever reasons, of a sine-sweep vibration-test philosophy for a complete spacecraft at the outset of a new space program preempts the full exploitation of this technology. Moreover, through an implicit reflection on *design criteria*, such a philosophy subjects both the configuration and the *structural* weight of the spacecraft to arbitrary and needless compromise.

Recent developments in analytical capability have been directed toward facilitating the *technical management*[5] of the dynamic-loads analysis of an integrated, multistage,

[5]This subject will be treated in greater depth in a future document.

space vehicle. Consideration has been given to the administrative and managerial discontinuities inherently associated with the procurements of the various stages. Pilot applications of these recent developments tend to support the feasibility of this type of approach to spacecraft structural design and testing in new programs.

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