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CAPABILITIES OF ELECTRODYNAMIC SHAKERS WHEN USED FOR MECHANICAL SHOCK TESTING

W. BRIAN KEEGAN

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ABSTRACT

This document presents the results of a research task to investigate the capabilities of electrodynamic vibrators (shakers) to perform mechanical shock tests. The simulation method employed was that of developing a transient whose shock response spectrum matched the desired shock response spectrum. Areas investigated included the maximum amplitude capabilities of the shaker systems, the ability to control the shape of the resultant shock response spectrum, the response levels induced at frequencies outside the controlled bandwidth, and the nonlinearities in structural response induced by a change in test level. In providing the detailed results of the investigation into this environmental simulation technique, this document complements the "Handbook for Conducting Mechanical Shock Tests Using an Electrodynamic Vibration Exciter," which has been issued as Supplement A to the Goddard Specification S-320-G-1.

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CAPABILITIES OF ELECTRODYNAMIC SHAKERS WHEN USED FOR MECHANICAL SHOCK TESTING

INTRODUCTION

In recent years, much attention has been focused on the mechanical shock environment for aerospace hardware. During this time the electrodynamic vibrator has become an increasingly useful tool in simulating this environment. Although the capabilities of shakers in simulating the vibration environment are well documented, many questions remained unanswered regarding their capabilities for mechanical shock simulation. As a result, the Structural Dynamics Branch of the Goddard Space Flight Center embarked on a research program to explore the extended capabilities of shakers to perform shock testing.

The method of simulating the mechanical shock environment on the shaker may take either of two forms: first, duplication of the time history of an actual flight data transient or second, synthesis of a time history whose shock spectrum matches, within some allowable tolerances, the shock response spectrum of the actual flight data transient. Although considerable effort has been devoted to the former method, it is the latter method which has been selected by Goddard for recommendation in our General Environmental Test Specification (Reference a). It is, therefore, this second method which was investigated during the course of the aforementioned research program.

The overall objective of this program was to evaluate the capability of the electrodynamic shaker and associated shock simulation equipment to produce a simulated shock environment by matching at some control point the shock response spectrum of the <u>simulated</u> environment to that of the <u>real</u> environment.

The specific objectives which had to be met in order to accomplish the overall objective mentioned above were:

(1) To ascertain the maximum attainable shock levels in the low (10 to 200 Hertz), middle (200 to 1000 Hertz), and high (1000 to 4000 Hertz) frequency ranges,

(2) To measure the shock spectrum levels induced at frequencies outside the bandwidth over which shock spectrum control was being exercised and to evaluate the shaping capability within the controlled bandwidth,

(3) To measure the nonlinearities in the shock spectrum of the time history induced at the control point as a function of the overall system gain, and

(4) To determine if two different time histories each possessing similar shock spectra at some control point near the test item/fixture interface induce responses throughout the test item that are similar on both a shock spectral and peak acceleration basis.

Due to limitations of facility availability as well as the availability of suitable hardware, this last objective was not accomplished. All other questions addressed, however, were satisfactorily resolved.

TEST PROGRAM

To accomplish the above objectives a comprehensive test program had to be outlined which covered all significant points related to the application of electrodynamic shakers to performing mechanical shock tests. Since all shock test requirements of the Goddard specification fall into one of two distinct classes, it was decided to conduct two separate test programs, one to investigate the low frequency area from 10 to 200 Hz encountered, for instance, when performing the Scout optional thrust axis transient test, and the other to investigate the middle and high frequency range from 200 to 4000 Hz encountered when performing a simulation of the pyrotechnic shock environment.

Low Frequency Test

The first of these test programs was the low frequency investigation. For this sequence, the test item was a "dummy" spacecraft fabricated specifically for this test program. Typical of Scout payload structural characteristics, it weighed 370 pounds and its center of gravity was 21 inches above the separation plane. Its first lateral resonant frequency was 15 Hz and the first longitudinal resonance was 47 Hz. The test article is illustrated in Figure 1.

For this sequence, the test equipment used included a MB-C125 electrodynamic vibrator, a Ling 60/100 amplifier, and the necessary peripheral equipment (see Reference b) to conduct an on the shaker shock test, including a waveform synthesizer and a real time shock spectrum analyzer. In brief, a waveform synthesizer is a device capable of producing independently adjustable outputs at frequencies from 10 to 4000 Hz with spacing between frequency components of one-third octave and capable of assembling these various frequency components into a pulse train that is repeatable with regard to both the time and amplitude relationships between these components.

The test sequence first involved simulating the Scout Launch Vehicle optional thrust axis transient. The design qualification level requirement for this specification is presented in Figure 2. As can be seen, the applied transient must

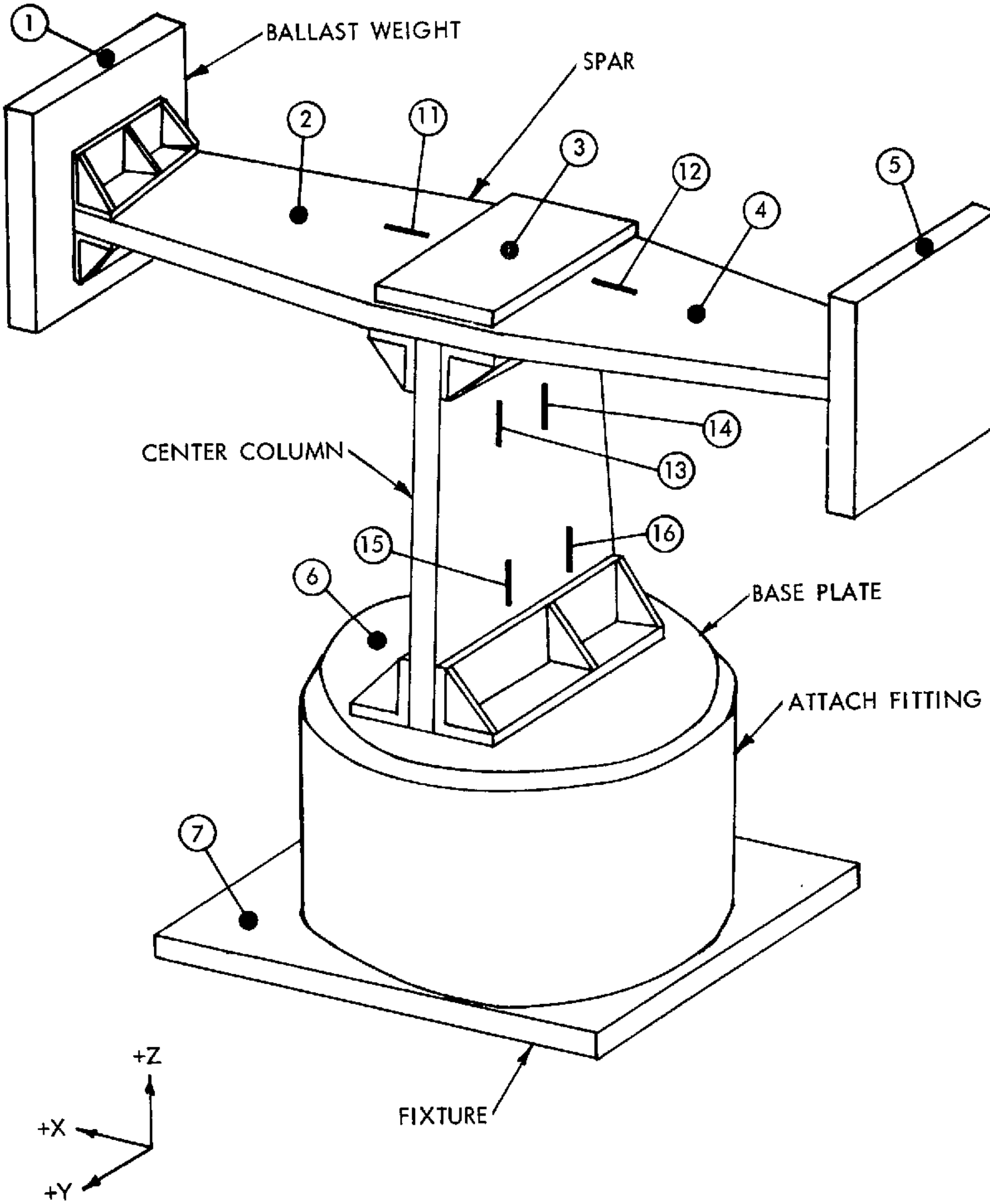

Figure 1. Test Item and Instrumentation Locations for Low Frequency Shock Investigation

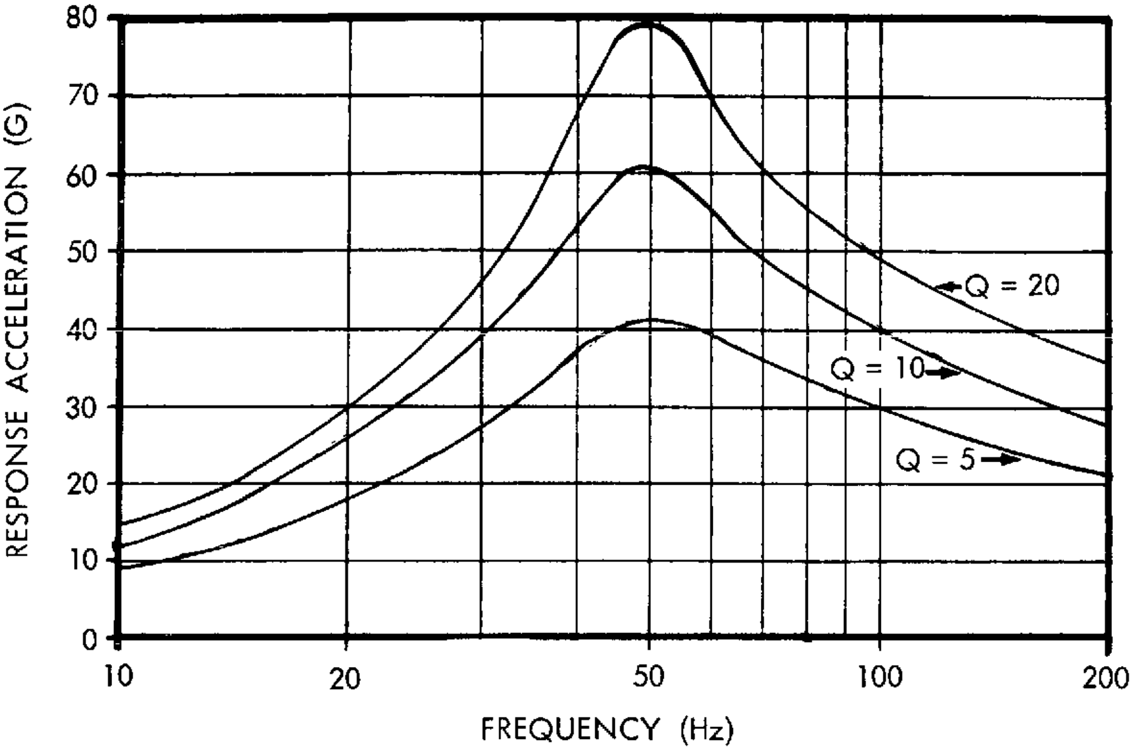

Figure 2. Scout Design Qualification Shock Specification used for Low Frequency Thrust Axis Shock Investigation

have a specified shock spectrum, within permissible tolerances, for three different damping ratios, corresponding to Q = 5, Q = 10, and Q = 20. A Run Schedule of this low frequency test sequence is presented in Table I. Run Numbers not listed in the table were either sinusoidal sweeps to obtain information about the dynamic behavior of the test item or preliminary shock runs identical to others listed in the table. Runs identified in the table as "equalized" were adjusted until the resultant shock spectrum shape was equal to that desired, within tolerance limits. Runs identified as "unequalized" were made simply after increasing the system master gain without regard to the resultant changes in shock spectrum shape. The initial time history was equalized such that its shock spectrum matched the 25 percent level of Figure 2 for each of the Q values required. The master gain was then increased in several steps, each time re-equalizing the shock spectrum shape, in order to serve as a measure of the non-linearities in the spacecraft dynamic response. Next, the same gain settings were repeated, but this time the shock spectrum shape was not reequalized at each level. This sequence continued until consistent shaker shutdowns were encountered in order to define the maximum capability of the shaker system. These shutdowns were a result of either the amplifier current interlock or the armature displacement interlock and while they inflicted no damage to either the shaker system or the test article, they prohibited the full duration of the time history from reaching the shaker head, thereby reducing significantly the resultant shock spectrum magnitude.

Table I

Run Schedule for Low Frequency Shock Investigation

Run	Axis	Description
11	Thrust	25% Scout Design Qualification Level, Equalized
12	Thrust	50% Scout Design Qualification Level, Equalized
14	Thrust	100% Scout Design Qualification Level, Equalized
18	Thrust	25% Scout Design Qualification Level, Equalized
19	Thrust	50% Scout Design Qualification Level, Unequalized
20	Thrust	100% Scout Design Qualification Level, Unequalized
21	Thrust	150% Scout Design Qualification Level, Unequalized
26	Thrust	25% 100 Hz Peak Spectrum, Equalized
27	Thrust	50% 100 Hz Peak Spectrum, Unequalized
28	Thrust	100% 100 Hz Peak Spectrum, Unequalized
29	Thrust	150% 100 Hz Peak Spectrum, Unequalized
30	Thrust	25% 25 Hz Peak Spectrum, Equalized
31	Thrust	50% 25 Hz Peak Spectrum, Unequalized
32	Thrust	100% 25 Hz Peak Spectrum, Unequalized
33	Thrust	75% 25 Hz Peak Spectrum, Unequalized
40	Lateral	25% Lateral Axis Shock Spectrum, Equalized
41	Lateral	50% Lateral Axis Shock Spectrum, Equalized
42	Lateral	100% Lateral Axis Shock Spectrum, Equalized
43	Lateral	150% Lateral Axis Shock Spectrum, Equalized
44	Lateral	50% Lateral Axis Shock Spectrum, Unequalized
45	Lateral	100% Lateral Axis Shock Spectrum, Unequalized
47	Lateral	150% Lateral Axis Shock Spectrum, Unequalized

Upon completion of the investigation of the capability of performing the Scout requirements, other low frequency capability was studied by shifting the shock spectra of Figure 2 both to the right and left by a factor of two along the frequency axis, thereby requiring the equalization of spectra which peaked at 100 Hz and 25 Hz respectively. Similar changes to the system gain as described above provided additional insight into the magnitude of nonlinearities encountered in the dynamic response of the shaker system.

After completion of this thrust axis investigation, it was desired to determine the low frequency shock capabilities in the lateral axis. For this, the test item was mounted on a hydrostatic bearing table. Otherwise, all equipment used was identical to that used for the thrust axis test. The Scout transient specification was not considered appropriate for this axis and therefore the shock specification used was that of the lateral axis Scout qualification sinusoidal vibration specification (see Figure 3). As can be determined from Reference b, the shock spectrum of a sinusoidal sweep is simply Q times the sinusoidal vibration level. In this axis, the gain level was also gradually increased until 150 percent of the qualification shock level was reached. Two series of tests were conducted, one reequalizing the spectrum shape at each increment and the other in which the spectrum shape was not reequalized.

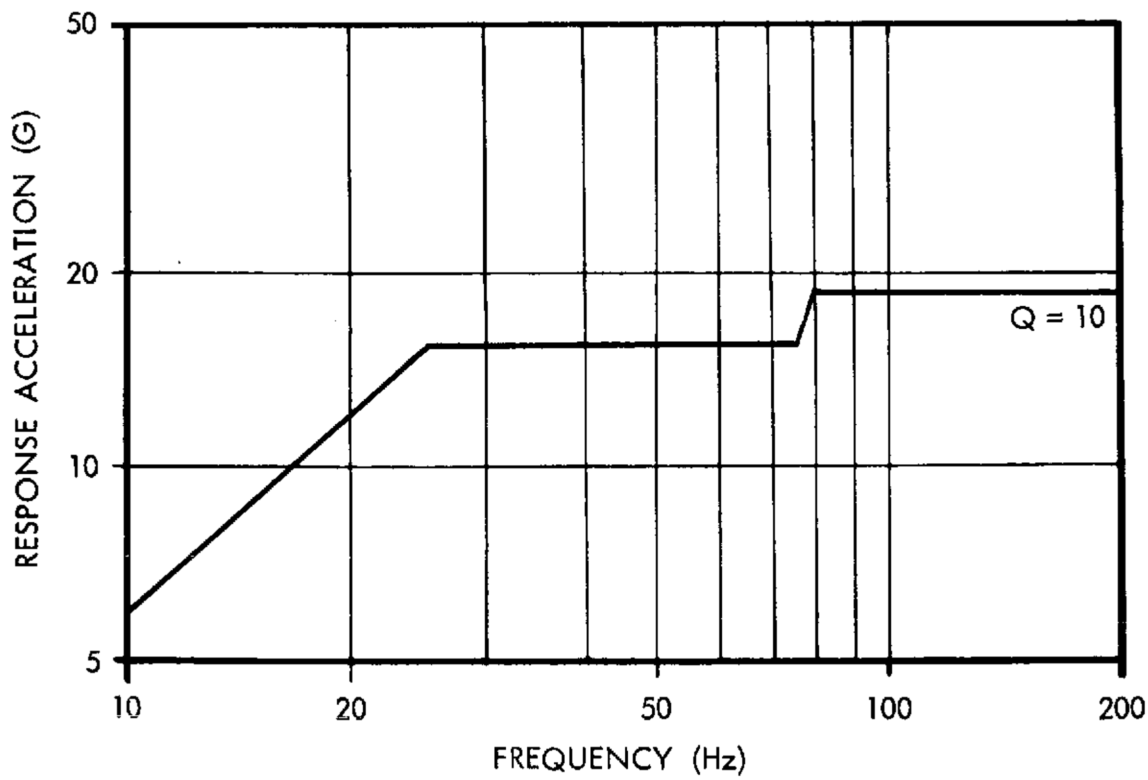

Figure 3. Shock Spectrum of Scout Design Qualification Vibration Specification used for Low Frequency Lateral Axis Shock Investigation

High Frequency Test

The second test program which formed a part of this research task was the high frequency investigation. For this, the structural model of the OSO-G spacecraft was used as the test item. It weighed 600 pounds and had the dynamic characteristics of a typical Explorer class satellite which is representative of spacecraft most commonly tested at Goddard. The spacecraft is illustrated in Figure 4.

For this test sequence, the test equipment used included an MB-C210 electrodynamic vibrator, an MB-5140 amplifier and the same peripheral shock test equipment utilized during the low frequency test program.

The test program revolved primarily around simulating the pyrotechnic shock environment induced by the Titan III-C launch vehicle. This is the highest system level shock test requirement of the Goddard General Environmental Test Specification, S-320-G-1 (Reference a). The design qualification levels for this specification are presented in Figure 5. A Run Schedule of this high frequency test sequence is presented in Table II. As before, Run Numbers not listed in this table were either sinusoidal sweeps to obtain information about the dynamic behavior of the test item or preliminary shock runs identical to others listed in this table. As can be seen from the listing, the initial time history was equalized such that its shock spectrum matched the 25 percent level of Figure 5. The console master gain was then increased incrementally, first to perform a series of runs without reequalizing the shock spectrum shape at each increment and then to perform a series of runs in which the spectrum shape was reequalized at each increment. This last sequence was continued until the maximum capabilities of the shaker system had been reached.

During this high frequency test program, as in the low frequency investigation, testing was performed in both one lateral and the thrust axis. Here, however, the same specification was used as a basis for testing in both axes. The only additional equipment used for lateral axis testing was the large lateral table, weighing approximately 550 pounds, and six hydrostatic bearing tables to provide near friction-free motion.

An additional task of this high frequency investigation was the attempt to measure the effect of the test item on the total system dynamics. It was wondered if the shock spectrum could be equalized with the test item off the shaker but with all other fixturing to be used mounted, since in pyrotechnic shock simulation the frequency range of the input energy is well above the resonant frequencies of the test item, and the test item therefore has a very low "apparent mass." As can be seen from Table II this was accomplished by equalizing the desired shock spectrum with the test item removed from the shaker and then after

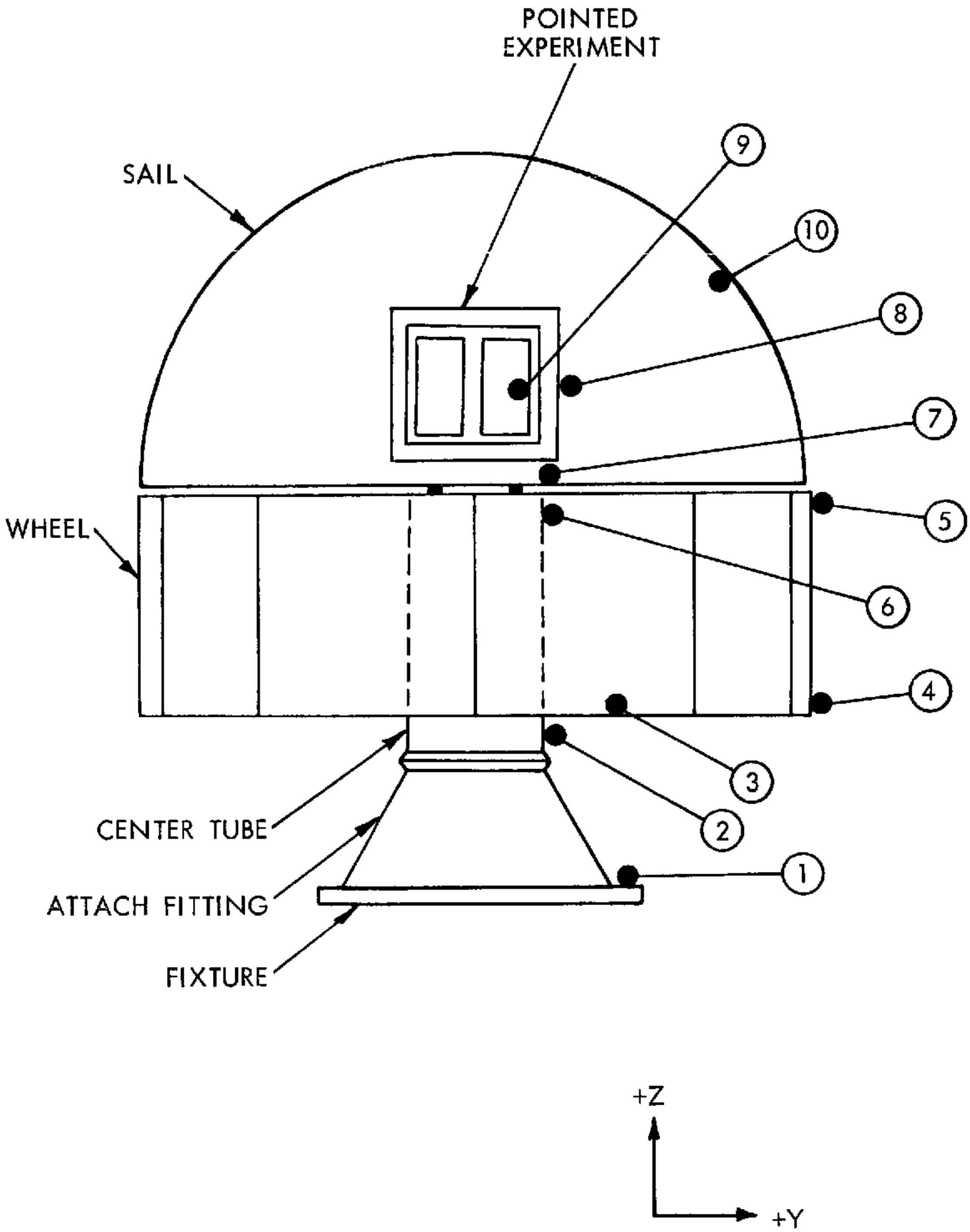

Figure 4. Test Item and Instrumentation Locations for High Frequency Shock Investigation

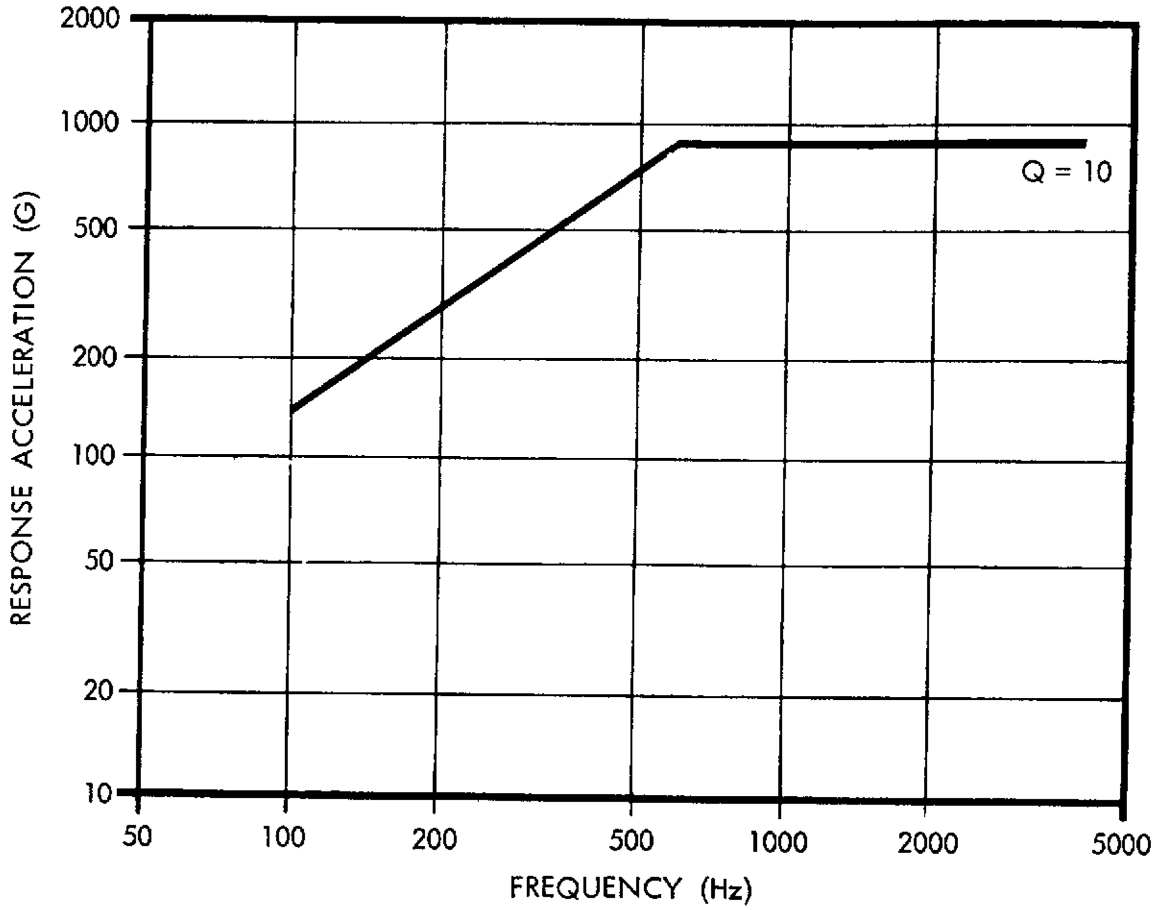

Figure 5. Titan III-C Design Qualification Shock Specification used for High Frequency Shock Investigation

reinstalling the test item on the fixture, applying the same voltage time history obtained from the previous equalization and calculating the shock spectrum of the resultant acceleration time history.

The results of all investigations conducted as a part of this research task are presented in a later section of this report.

DYNAMIC INSTRUMENTATION AND DATA ANALYSIS

A total of 20 data channels were recorded during both the low and high frequency test sequences. Instrumentation for the low frequency test consisted of 13 crystal accelerometers and 7 strain gages. The strain gages were wired in pairs, some so as to be sensitive to only bending stresses and some to only tension-compression loads. The mounting locations are illustrated in Figure 1 and described in Table III and were selected to provide an adequate picture of the shock input and its transmission through the structure.

Table II

Run Schedule for High Frequency Shock Investigation

Run	Axis	Description
3	Lateral	25% Titan III-C Design Qualification Level, Equalized
4	Lateral	50% Titan III-C Design Qualification Level, Unequalized
5	Lateral	100% Titan III-C Design Qualification Level, Unequalized
6	Lateral	50% Titan III-C Design Qualification Level, Equalized
8	Lateral	100% Titan III-C Design Qualification Level, Equalized
10	Lateral	100% Titan III-C Design Qualification Level, Equalized (Repeat of Run 8)
11	Lateral	100% Titan III-C Design Qualification Level, Equalized, Spacecraft Removed
14	Lateral	Same Voltage Input as Run 11, Spacecraft Reinstalled
15	Lateral	Same Voltage Input as Run 11, Spacecraft Reinstalled
18	Thrust	25% Titan III-C Design Qualification Level, Equalized
19	Thrust	50% Titan III-C Design Qualification Level, Unequalized
20	Thrust	100% Titan III-C Design Qualification Level, Unequalized
22	Thrust	50% Titan III-C Design Qualification Level, Equalized
23	Thrust	100% Titan III-C Design Qualification Level, Equalized
24	Thrust	100% Titan III-C Design Qualification Level, Equalized (Repeat of Run 23)

Table III

Instrumentation Information for Low Frequency Shock Investigation

Location	Number	Transducer Type
+X Spar - End of Span	1X 1Y 1Z	Σ2221 Acc. Σ2221 Acc. Σ2221 Acc.
+X Spar - Mid Span	2Z	Σ2221 Acc.
Spar Centerline	3X 3Z	Σ2221 Acc. Σ2221 Acc.
-X Spar - Mid Span	4Z	Σ2221 Acc.
-X Spar - End of Span	5X 5Y 5Z	Σ2221 Acc. Σ2221 Acc. Σ2221 Acc.
Spacecraft Base Plate - Top of Attach Fitting	6X 6Z	Σ2221 Acc. Σ2221 Acc.
Input Monitor - Base of Attach Fitting	7X 7Z	Σ2224 Acc. Σ2224 Acc.
+X Spar - Inner End	11B	Bending Bridge
-X Spar - Inner End	12B	Bending Bridge
Center Column - Mid Height	13B	Bending Bridge
Center Column - Mid Height	14T	Tension Bridge
Center Column - Base	15B	Bending Bridge
Center Column - Base	16T	Tension Bridge

For the high frequency test, 20 crystal accelerometers were mounted at various locations around the structure and at the spacecraft/fixture interface with the same measurement objective as the low frequency program. These locations are illustrated in Figure 4 and described in Table IV.

Data reduction in the form of acceleration shock response spectra was performed for all in-axis channels for all runs listed in Tables I and II. Data from selected off-axis channels was also reduced for selected runs. All shock spectrum computations were made for $Q = 10$ with a spectral resolution of one-fifteenth octave and all data analysis and interpretation was based on these shock spectral results.

Table IV

Instrumentation Information for High Frequency Shock Investigation

Location	Number	Transducer Type
Base of Attach Fitting	1Y	Σ2225 Acc.
	1Z	Σ2225 Acc.
Base of Center Tube	2Y	Σ2225 Acc.
	2Z	Σ2225 Acc.
Wheel, Compartment 2 - Lower Outboard Edge	3Y	Σ2221 Acc.
	3Z	Σ2221 Acc.
Wheel, Compartment 3 - Lower Outboard Edge	4Y	Σ2221 Acc.
	4Z	Σ2221 Acc.
Wheel, Compartment 3 - Upper Outboard Edge	5Y	Σ2221 Acc.
	5Z	Σ2221 Acc.
Wheel, Azimuth Drive Assembly	6Y	Σ2221 Acc.
	6Z	Σ2221 Acc.
Sail, Azimuth Casting at Bearing Interface	7Y	Σ2221 Acc.
	7Z	Σ2221 Acc.
Sail, Azimuth Casting at Elevation Trunnion	8Y	Σ2221 Acc.
	8Z	Σ2221 Acc.
Sail, Elevation Casting at Trunnion	9Y	Σ2221 Acc.
	9Z	Σ2221 Acc.
Sail, Outboard Equipment Location	10Y	Σ2221 Acc.
	10Z	Σ2221 Acc.

RESULTS

The results of this test program were many and varied. In this section, they will be treated as they pertain to the specific objectives of the program. Therefore, while data comparisons will be presented, individual presentation of the data obtained will not be made. All data acquired, however, is available from the author if any reader desires to study the information further.

Perhaps the most significant result was the publication under separate cover of a "Handbook for Conducting Mechanical Shock Tests Using an Electrodynamic Shaker" (Reference b) which has been issued as Supplement A to the Goddard General Environmental Test Specification, S-320-G-1 (Reference a). This handbook provides guidance for setting up and conducting shock tests in conformance with the aforementioned specification and includes information on the technical background pertaining to shock spectra, a list of the necessary equipment, and a suggested sequence of equalization of the pulse train so as to minimize the exposure time of the test item to the environment during test setup. As such, the handbook treats the problems associated with the implementation of testing to shock spectrum requirements and utilizes the results of all the various questions investigated during the course of this research program.

As stated in the objectives, evaluating the overall capability of electrodynamic shakers to perform mechanical shock testing necessitated subdividing this objective into several areas which could be addressed individually.

Maximum Attainable Shock Spectrum Levels

The first of these was the determination of the maximum shock levels which could be achieved in the low, middle and high frequency ranges. During the investigation of low frequency shock testing, as encountered during the Scout thrust axis transient test, a peak time history of 38 G was produced in the thrust axis using the MB-C125 shaker driven by the Ling 60/100 amplifier rated at 10,000 pounds peak force. The time history and the resultant shock spectrum of this pulse are presented in Figures 6 and 7 respectively. This data was taken from Run 21 (from Table I) which was subsequently determined to be the one which defined the maximum low frequency capabilities without causing a shaker system shutdown. For comparison purposes, the Scout thrust axis transient design qualification shock spectrum requirements for $Q = 10$ are also shown in Figure 7.

The total driven weight for this run was 500 pounds, including the shaker armature, fixturing and test item. The rigid body force rating of the shaker/amplifier combination would predict only 20 G with this weight, whereas approximately

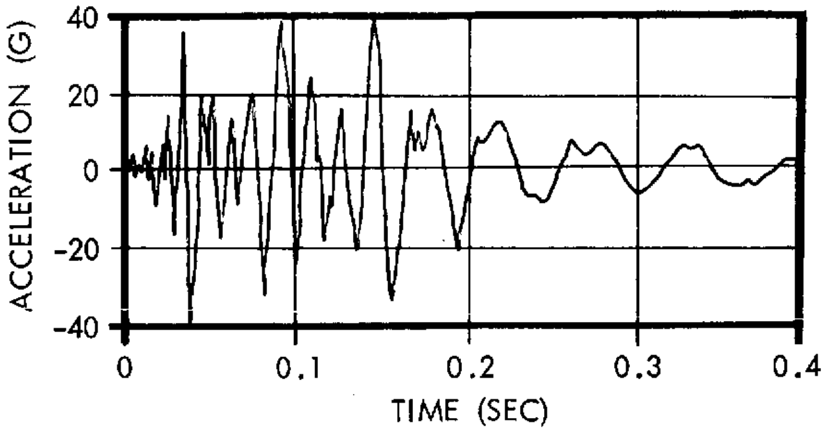

Figure 6. Maximum Attainable Time History During Low Frequency Shock Investigation

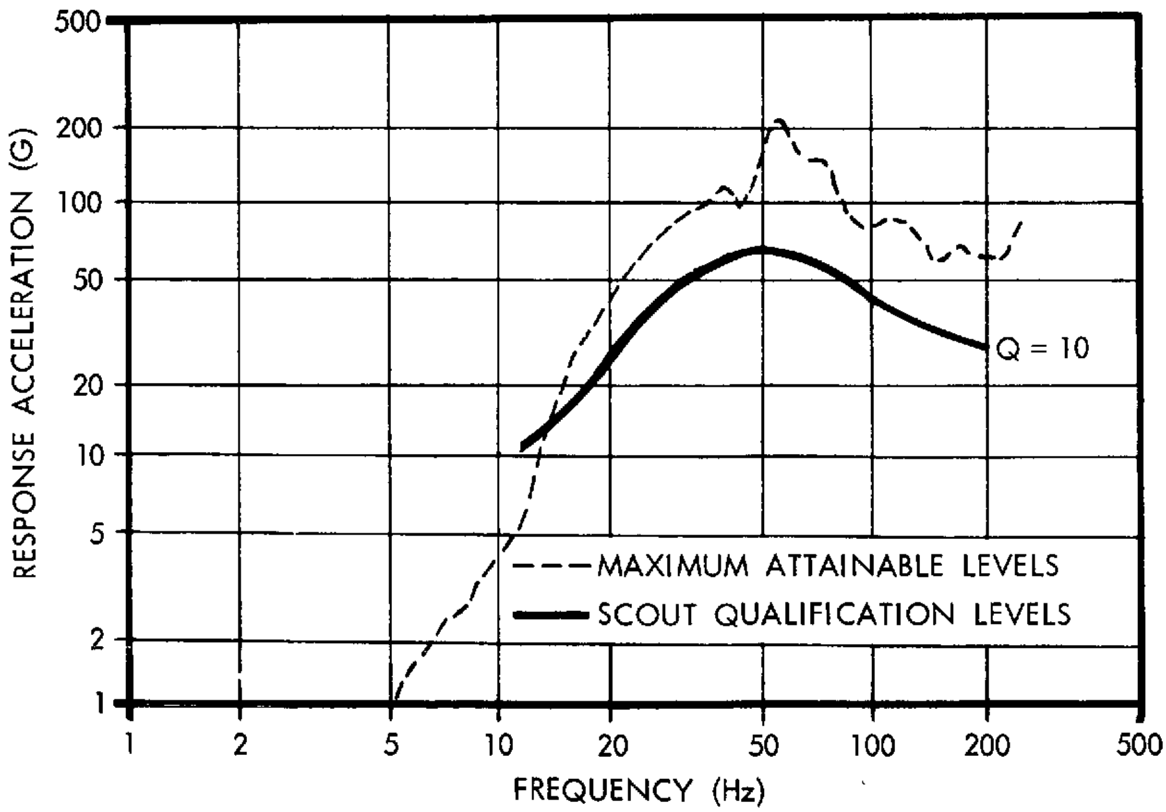

Figure 7. Maximum Attainable Shock Spectrum During Low Frequency Shock Investigation

twice that much was capable of being produced. In the frequency range from 40 to 100 Hz, where the maximum energy is required for the Scout transient test, the apparent mass of the test item is at least equal to its weight. Therefore, no increase in apparent shaker force should have been obtained as a result of the test item's "apparent mass" being less than its actual mass. It is felt that the reason for being able to obtain as much as 38 G when the rigid body force rating would predict only 20 G is that the shaker amplifier is capable of producing currents significantly greater than its rated capacity for short durations, thereby effectively increasing the rated force pound capacity of a system for transient testing. These results would indicate that the apparent force capability of a shaker system when used for low frequency transient testing is approximately twice its rigid body force rating. Whether or not this factor of two would apply to all shaker systems is only speculation; nevertheless, it is felt that these results at a minimum indicate that if the ability of a system to meet a certain specification appears to be marginal based on rigid body force consideration, it is likely to be able to satisfactorily meet the requirements. Although the above discussion made use of information obtained during thrust axis testing, evaluation of data from lateral axis testing produced essentially the same results.

During the research investigation to determine the maximum capabilities for shaker shock testing in the mid and high frequency range, peak time history accelerations of approximately 300 G were produced in the lateral axis using the MB-C210 shaker driven by the MB-5140 amplifier rated at 28,000 pounds peak force. The time history and the resultant shock spectrum are shown in Figures 8 and 9, respectively, and were obtained during Run 11 (from Table II). As before, this was the maximum possible input which did not result in a shaker system shutdown. For comparison purposes, the design qualification requirements of the Titan III-C specification (the highest requirements of S-320-G-1) are also presented in Figure 9.

The total driven weight was 1150 pounds including the shaker armature, fixturing and test item. The rigid body force rating of the shaker/amplifier combination would predict only 25 G with this weight, but this was obviously exceeded by a large factor. The most likely reason for this is that the resonant frequencies of the test item and fixturing were below the frequencies at which the specification required most of the energy. The spectrum shape illustrated in Figure 9 required the most energy in the 800 to 2000 Hz region. The apparent mass of the test item was relatively small at these frequencies since the highest test item resonance was 600 Hz. Thus, high G level transients could be generated with small forces. Similar results were obtained during high frequency shock testing in the thrust axis. These results would indicate that the apparent force capability of a shaker system when used for shock testing in the mid and high frequency range is approximately ten times its rigid body force rating, since

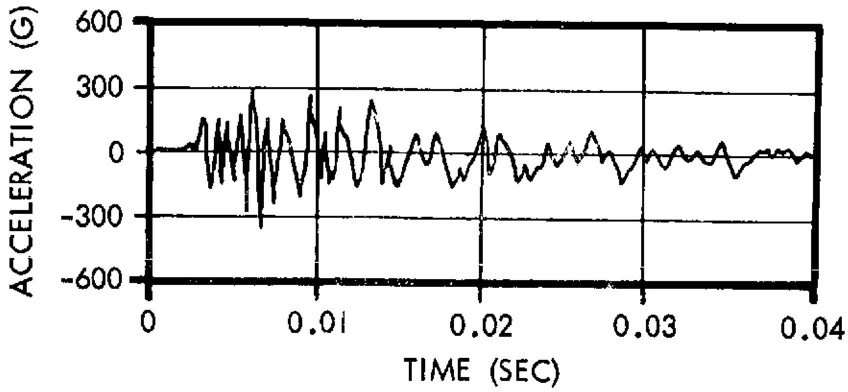

Figure 8. Maximum Attainable Time History During High Frequency Shock Investigation

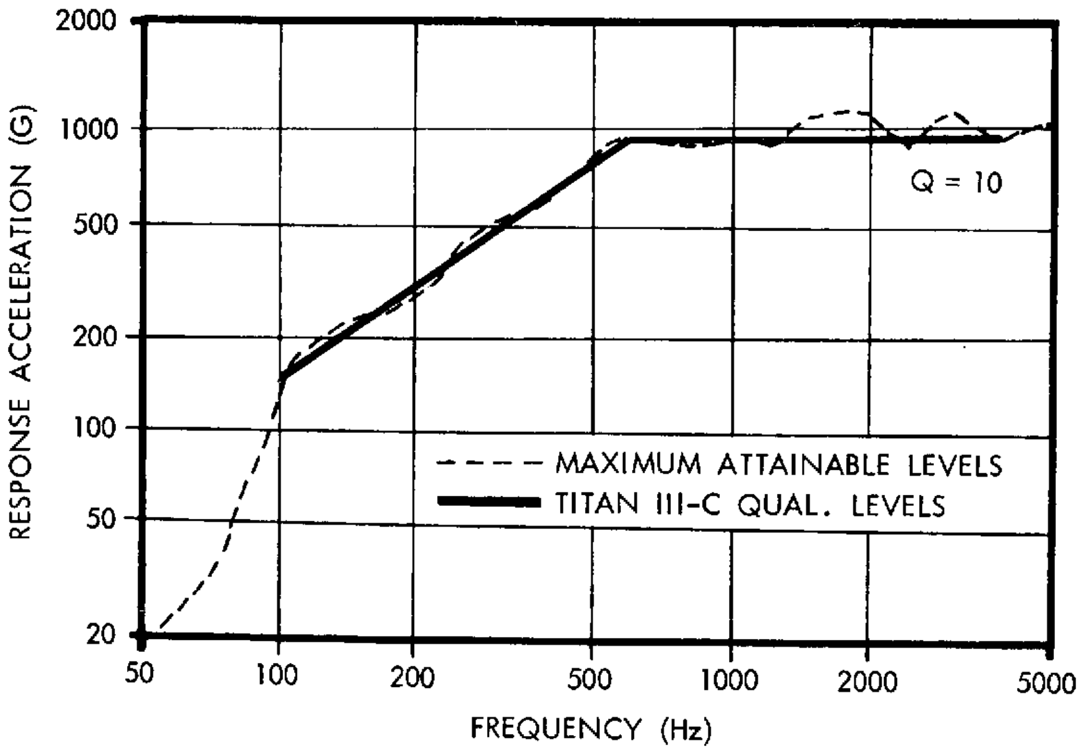

Figure 9. Maximum Attainable Shock Spectrum During High Frequency Shock Investigation

300 G peaks were attainable when only 25 G peaks were predicted. While blanket use of this factor of 10 is not recommended, it is felt that these results do indicate that large electrodynamic shaker systems are capable of producing transients with peak G levels of approximately 300 G and whose shock spectra for a Q = 10 damping value approach 1000 G in the high frequency range, thereby making them capable of meeting the most severe requirements of the launch vehicle induced shock simulation specification of S-320-G-1. Evaluation of data for the thrust axis showed nearly identical maximum levels thereby substantiating the results presented above.

Shock Spectrum Shaping Capability

The next objective towards which evaluation of the test data was directed was that of shock spectrum shaping capability and inputs at frequencies other than those that are required by the governing specification.

The ability to shape the shock spectrum is limited by two factors. The first of these is the shock spectrum shape of a single frequency component of the pulse train. Each frequency component is controlled by a fixed frequency filter whose amplitude is independently adjustable. These filters are spaced at regular frequency increments (usually one-third octave) and each is then relied upon to control the shock spectrum in the vicinity of its center frequency. The shock spectrum of each of these frequency components peaks at its center frequency and rolls off to either side. The amount of this rolloff is determined by the amplitude modulation characteristics of the voltage output of each filter. Each of these filters will control the shock spectrum in the vicinity of its own center frequency, f, unless the desired shock spectrum value at that frequency is so much lower than that desired at some adjacent filter frequency that the energy input at the adjacent filter controls the spectrum in the vicinity of f as well as in the vicinity of its own center frequency. Results have indicated that spectra with increasing slopes of no greater than 30 dB/octave and decreasing slopes of no greater than 10 dB/octave can be satisfactorily equalized with little trouble.

Another factor affecting the ability to shape the shock spectrum is the dynamic signature of the test item/shaker combination. The specification requires that the shock spectrum magnitude be within the allowable tolerances of +50 and -10 percent for the specified damping value with at least a one-third octave resolution for spectral computations. Since most commercially available waveform synthesizers have a one-third octave spacing between the frequencies of their transients, it is unreasonable to require better than one-third octave resolution on an analysis verifying that a particular time history complies with the specification. However, because of the effects of system dynamics and for the protection of the test item, it is recommended that the shock spectrum of the applied transient be calculated with one-sixth octave resolution as the pulse is equalized and as the level is gradually increased. This recommendation is made in order to avoid inadvertent excitation of a test item resonance that lies midway between two one-third octave center frequencies. It is possible that by exciting such a test item resonance, the shock spectrum of the input pulse may be well above specification at the frequency of the test item resonance. While the resultant test may meet the requirements of the specification (that is to say that the spectrum may be within tolerance at the one-third octave center frequencies), the effects of this potential overtest at other frequencies must be considered before subjecting the test item to a full level shaker shock test.

Inputs at Frequencies Outside Desired Bandwidth

As for extraneous inputs at frequencies outside the desired frequency range, we have found that the pulse train output from the shock synthesizer is sufficiently controllable to prevent any such problem from occurring. It is still possible, however, for transients at frequencies within the range of the specification to induce responses in the structure at frequencies outside that of the specification range which may cause the shock spectrum to have a value significant enough that it cannot be ignored. Cases in which this problem may arise are difficult to predict in advance and the spectral magnitudes at some undesired frequency are even more difficult to predict. The best advice that can be given is to proceed cautiously. While equalizing at low-level an analysis of the shock spectrum over the entire bandwidth capability of the analyzer should be made in order to assess the spectral values outside the specification bandwidth. If high levels exist at undesired frequencies and attempts to eliminate them by special electronics are unsuccessful, then a determination must be made either that the overtest will have no adverse effects on the test item, in which case testing may proceed, or that the overtest cannot be tolerated, in which case some other test method must be employed. In the actual circumstances encountered to date these potential problems have been found to be real but workable and without exception sufficiently satisfactory equalization has been achieved to permit shaker shock testing to proceed.

Measurement of Non-Linearities

The next question addressed was that of the nonlinearities that resulted in the shock spectrum of the input time history when applying an increase in the output gain of the waveform synthesizer. As discussed in Reference b, a good estimate of the expected spectral nonlinearities is essential to the equalization process. The results of this nonlinearity investigation are presented in Figures 10 thru 13. These figures contain information acquired during both the longitudinal and lateral axes for both the high frequency and low frequency shock investigations.

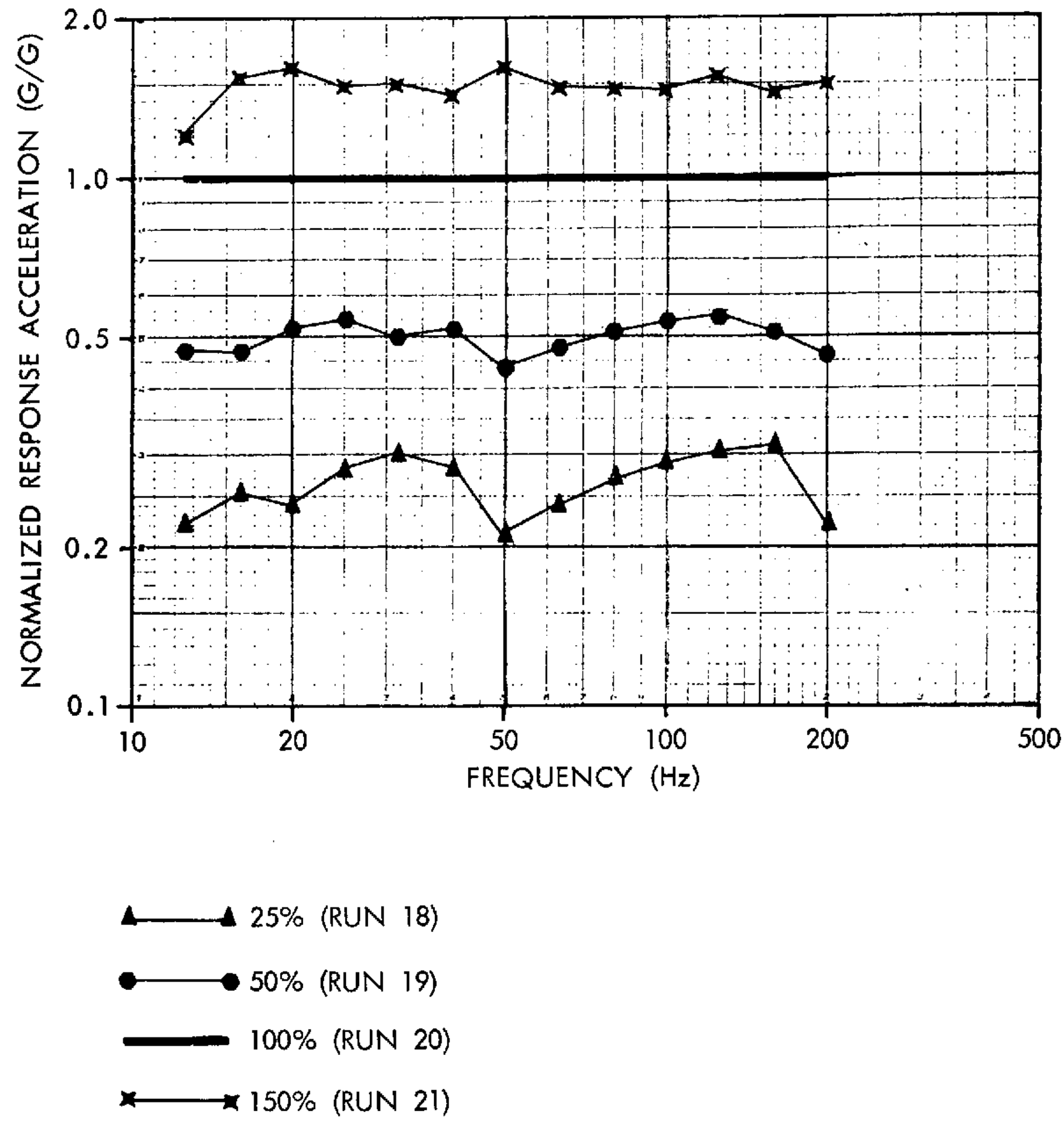

Figure 10. Results of Linearity Measurements During Thrust Axis Low-Frequency Shock Investigation (Data from Accelerometer 7Z)

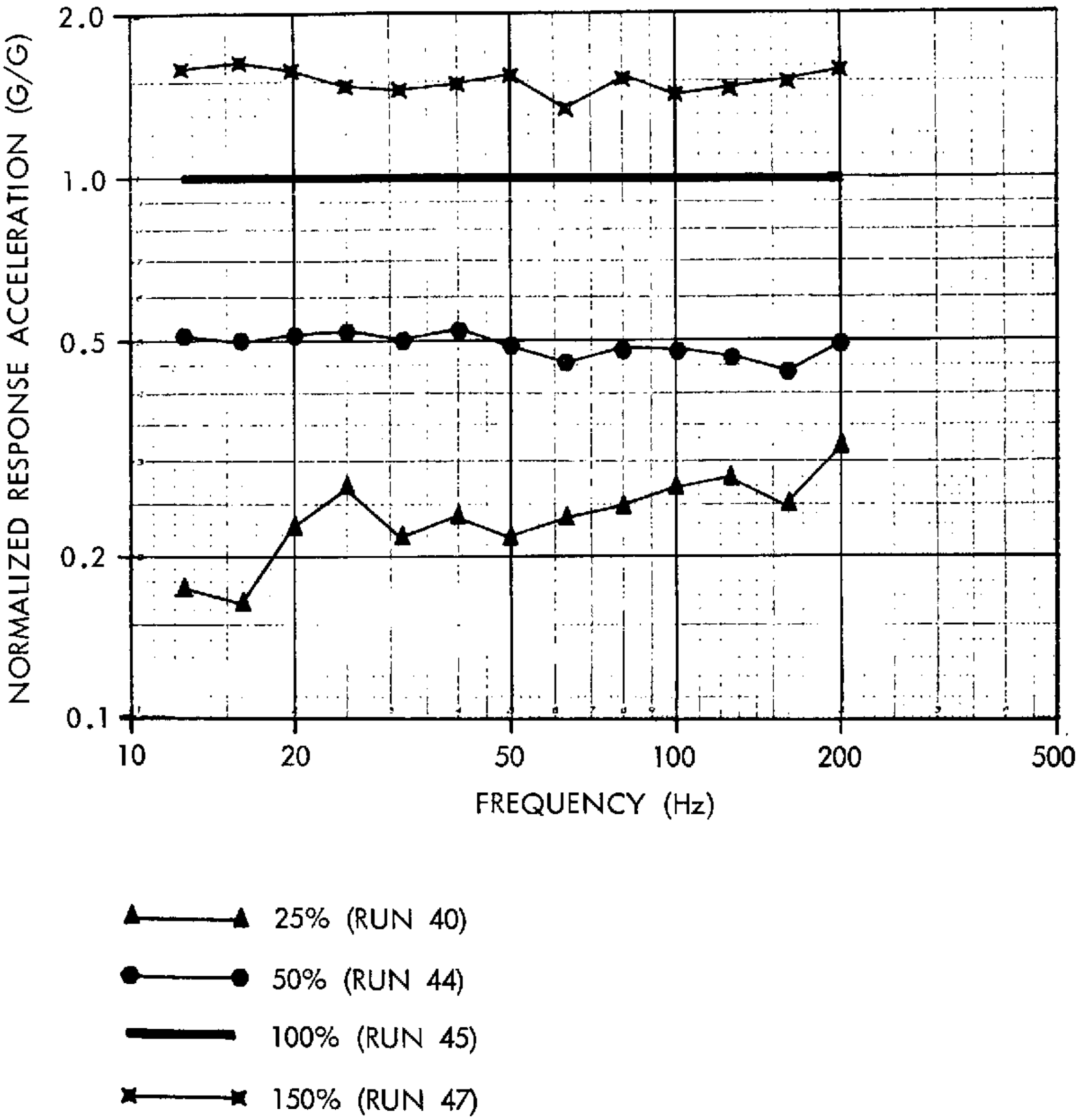

Figure 11. Results of Linearity Measurements During Lateral Axis Low-Frequency Shock Investigation (Data from Accelerometer 7X)

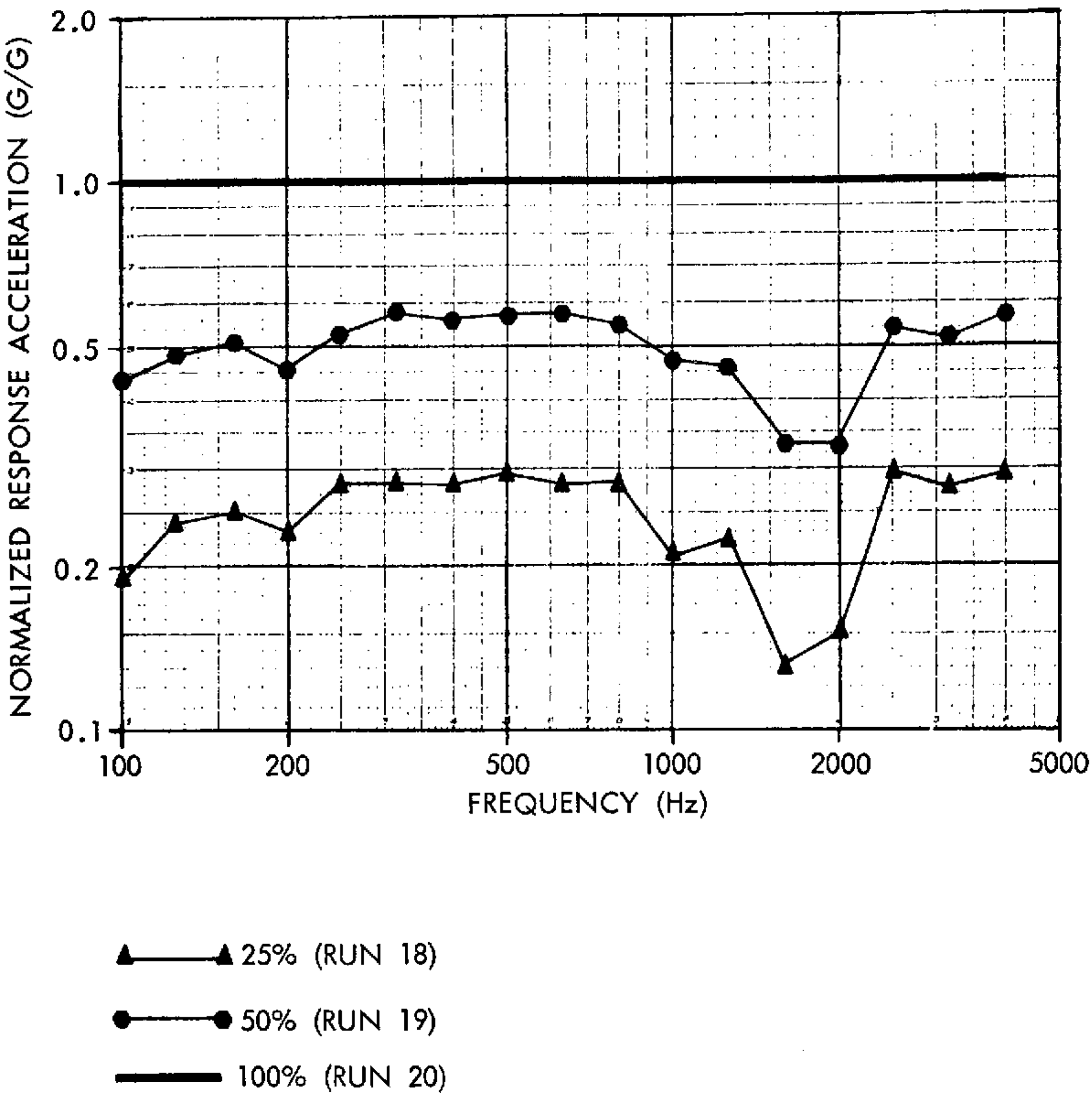

Figure 12. Results of Linearity Measurements During Thrust Axis High-Frequency Shock Investigation (Data from Accelerometer 1Z)

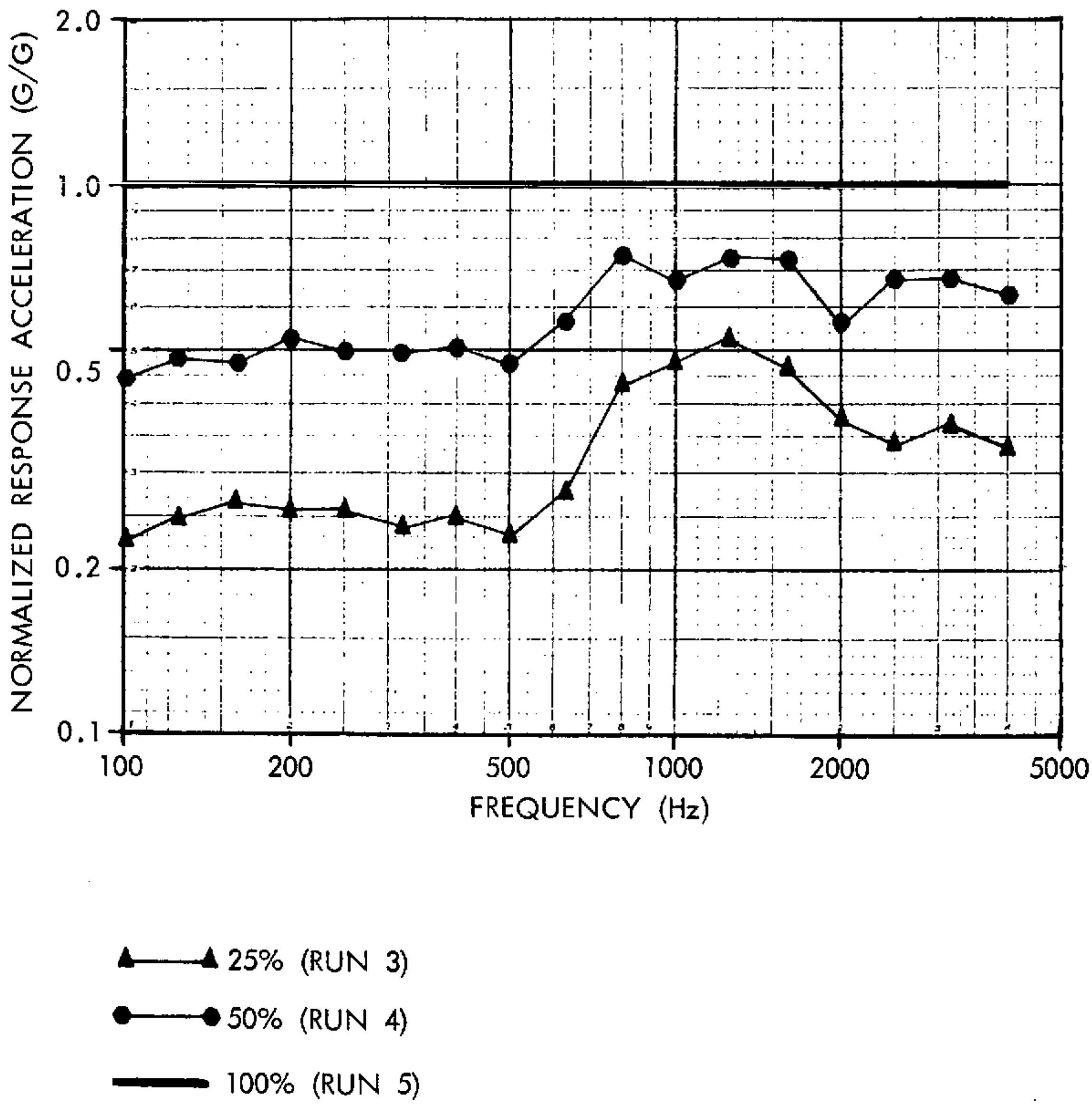

Figure 13. Results of Linearity Measurements During Lateral Axis High-Frequency Shock Investigation (Data from Accelerometer 1Y)

The data presented was taken from the indicated runs and was normalized to the 100 percent run. Initially, the spectrum had been equalized to 25 percent of the maximum desired spectrum. The 50 percent, 100 percent and 150 percent unequalized runs were obtained by raising the master gain control of the waveform synthesizer the necessary amount and applying the resultant voltage output to the test system. As can be seen throughout the majority of the spectrum, the response is quite linear with the change in spectral magnitude being within 10 percent of the change in gain magnitude. In the frequency ranges where appreciable nonlinearities are present (they approach 25 percent and occur at frequencies associated with shaker/test item system resonances), they are at least repeatable. That is to say that the percentage of nonlinearity observed when going from 25 percent to 50 percent is the same as observed when going from 50 percent to 100 percent, and when going from 100 percent to 150 percent. As mentioned in Reference b, as long as the magnitude of the nonlinearities is predictable, satisfactory equalization can be readily achieved.

As for the question of equalizing the shock spectrum with the spacecraft off the shaker but all necessary fixturing mounted, this proved to be unsatisfactory. It has been determined that if the test item weight is more than 10 percent of the total driven weight, it will have a significant enough effect on the dynamic response of the system that satisfactory equalization cannot be achieved without the test item in place during the equalization process.

CONCLUSIONS

The major conclusion which can be drawn is that the electrodynamic shaker is indeed a useful tool for conducting mechanical shock tests. As a result of this research program, several questions concerning the use of shakers for this purpose have been answered including their maximum capabilities and hence, their limitations. Principally it has been determined that shaker systems can generate shock amplitudes up to twice their rated force capability for low frequency testing (below 200 Hz) and up to 10 times their rated capability for high frequency testing (200 to 4000 Hz) without adversely affecting the shaker system or test item. There has also been developed a systematic approach to setting up and conducting shock tests so as to minimize the risk of the test item being exposed to a potentially damaging overtest.

REFERENCES

(a) General Environmental Test Specification, Goddard Specification S-320-G-1, dated October, 1969.

(b) Handbook for Conducting Mechanical Shock Tests Using an Electrodynamic Vibration Exciter, S-320-G-1, Supplement A, dated June, 1973.