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DEVELOPMENT OF STRUCTURAL DYNAMIC TEST ENVIRONMENTS FOR SUBSYSTEMS AND COMPONENTS

Robert J. Coladonato
Goddard Space Flight Center

SUMMARY

Structural dynamic environmental test levels were developed for the Thematic Mapper instrument, components of the Tandberg-Hanssen instrument, and components of the International Ultraviolet Explorer (IUE) spacecraft using NASTRAN structural models and test data. Both static and dynamic NASTRAN analyses were used. The model size required could be as small as 300 degrees of freedom for the static analysis and as large as 1000 degrees of freedom or more for the high frequency dynamic analysis. An important step in the development of the levels is model verification by test. The launch environments that generally dictate many important features of the design of an instrument or component are steady state acceleration, sinusoidal vibration, and random vibration. These are the environments that the analyst should examine closely when determining the appropriate test levels.

INTRODUCTION

Instruments and components that are designed for aerospace applications must function satisfactorily after being exposed to the launch environment. In order to gain a high level of confidence that the instrument will function satisfactorily after launch, the instrument is subjected to testing which attempts to simulate the conditions produced by the launch. The principal types of structural/dynamic testing used are sinusoidal vibration, random vibration, acoustic noise, shock, and steady state acceleration. These environments are normally defined or specified at the spacecraft level and the environmental test levels for the instrument typically have to be determined through test and/or analysis. These levels are influenced by the dynamic characteristics of the spacecraft. Once the test levels for the instrument are established, one can proceed one more step and generate the test levels for components mounted within the instrument. The test levels for the components are then a function of the dynamic characteristics of the instrument. Figure 1 provides a typical environmental test and analysis plan.

The test levels for the instrument or components can be determined by performing the appropriate analysis using NASTRAN structural models. Alternately, test levels can also be established from actual test data obtained during spacecraft system testing of the hardware. However, in most cases, testing of the spacecraft hardware does not occur until sometime after the design levels have been established for the instrument or component. When test data are available, however, they are used to evaluate the test levels that have been previously determined through analysis and these levels are updated or modified as deemed necessary. The test data should also be used to examine the veracity of the NASTRAN model. An attempt should always be made to achieve good correlation between model predictions and actual test data.

NASTRAN MODELS

Model Size

The size of the NASTRAN model that is required in terms of degrees of freedom is dependent upon the type of analysis that one is performing. The analysis can be divided into two general types, static analysis and dynamic analysis. Static analysis is used to simulate the steady state acceleration condition while dynamic analysis is used to simulate sinusoidal vibration, random vibration, acoustic noise and shock. For static analysis a NASTRAN model size of between 300 and 500 degrees of freedom is normally adequate for determining critical loads for most instruments. However, if one wishes to determine stresses in sensitive areas of the instrument, a more detailed model may be required. The problem with a detailed model is that it takes a long time to generate and then it takes a long time to run on the computer. A preferred technique for static analysis is to determine the critical loads from the smaller 300 to 500 degree of freedom model and then perform a detailed hand calculated stress analysis of the parts that are most sensitive.

For dynamic analysis the size of the model required depends upon the particular environment that is being simulated. Sinusoidal vibration test specifications cover frequencies up to 200 Hertz (Hz), and a model of between 300 and 500 degrees of freedom for an instrument is usually adequate. Random vibration specifications contain frequencies up to 2000 Hz and shock contains frequencies up to 4000 Hz. For these environments, a much more detailed model is necessary, possibly 2000 to 3000 degrees of freedom or more. The larger detail is necessary to provide confidence that the high frequency modes are realistically represented.

Acoustic noise contains frequencies up to 10,000 Hz and would require an extremely detailed model for accurate predictions. Acoustic noise is also a very complex environment to represent analytically and this type analysis is rarely performed. Part of the reason for not doing acoustic noise analysis is that historically it has been observed that it does not produce significant structural loads except on thin filmed windows or items that have large areas and low masses such as solar arrays. For these items an acoustic test is recommended. The foregoing discussion demonstrates that before the analyst generates a NASTRAN model, he should determine what the use of the model is really going to be and then decide upon an appropriate size. Perhaps it may be advantageous or even necessary to produce models of different sizes.

Model Verification by Test

The predictions from the model should be checked against actual test data as early in a program as possible. One needs to run an analysis using the model which represents the test configuration of the hardware. The test does not have to be a very severe high level test. Preferrably, it should be a low level test. A static load test where loads are applied at particular points on the instrument and deflections are measured can be used for model verification. To verify the dynamic characteristics of the model, a low level sinusoidal sweep can be done on the instrument with response data recorded on magnetic tape. The data can then be analyzed by plotting acceleration levels versus frequency and comparing these to predictions from the model. Also, coincident and quadrature plots versus frequency can be made to determine mode shapes and modal damping. Another test that can be used for dynamic verification is the modal survey test. In this test the instrument is excited by a low level input, generally random vibration. There are several automated modal survey test

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packages which store data from the test and then compute the mode frequency, mode shape, and modal damping automatically as well as display the mode shape on a screen.

Regardless of the testing technique used to verify the model, the knowledge that the model agrees well with test data is very reassuring. Once good correlation is obtained between model predictions and test data, the model can be used with confidence to evaluate the effect of design changes or to predict responses to various types of inputs. With the advent of the Space Shuttle the trend seems to be a deemphasis on qualification type structural testing with more reliance placed on predictions by analysis. However, this trend should not be interpreted to mean that no testing need be done. Testing to provide assurance of model veracity is still very important.

NASTRAN ANALYSIS METHODS

Steady State Acceleration

The steady state acceleration levels are defined in terms of gravitational acceleration units (g's) for the thrust and lateral directions. For example, 16.8 g's thrust and 3.0 g's lateral are typical for a Delta launched payload. The static analysis, Rigid Format 1, is used for steady state acceleration analysis. The most flexible way to run the analysis is to apply a 1.0 g load in each of the three orthogonal axes and then use subcase combinations (SUBCOM) to obtain the desired combination of loads.

Sinusoidal Vibration

The sinusoidal vibration analysis is normally performed using frequency response analysis. Either the direct formulation, Rigid Format 8, or the modal formulation, Rigid Format 11, can be used. The modal formulation is preferred because an eigenvalue analysis can first be performed and the modes saved on tape. This information, after checking, is used in a restart for the frequency response analysis.

The sinusoidal vibration test levels are defined as g's versus frequency and the frequency range is usually 5 Hz to 200

Hz. To run the analysis one can input the sinusoidal levels as defined in the specification and observe the response levels at points of interest. However, a more informative method is to input a constant unit acceleration and observe the response at the points of interest because using a constant input draws a much cleaner picture of the response characteristics.

The magnitude of the responses depends upon the value that is chosen for structural damping and hence modal amplification (Q) since modal Q equals the reciprocal of structural damping. Previous testing of instruments and components has shown that a modal Q of 15 is generally a conservative assumption for analysis. Assuming modal Q's greater than 15 quite frequently results in very high response levels and consequently unnecessary design changes. As a general rule of thumb, response levels greater than 20 g's would not be expected due to the dynamics of the launch environment. Therefore, unless there is substantiating evidence available, one should not assume Q's too high in the analysis.

Another variable in the frequency response analysis is the frequency at which response calculations are made. The frequency can be defined by a tabular listing of discrete frequencies, a linear spacing where a frequency increment is chosen, or a logarithmic spacing where the number of logarithmic intervals between the first and last frequency is chosen. It is important for one to pick the proper frequencies for the response calculations so as not to miss any peaks that occur. Using the modal formulation one can accomplish this by first doing an eigenvalue analysis, restarting, and then including all of the modal frequencies, as well as frequencies on either side, in a tabular listing of frequencies to be used for the response calculations. For the case of linear or logarithmic spacing the required frequency increment or the number of logarithmic intervals can be determined analytically. For example, assuming a Q of 15, in order to be sure that the calculated response is at least 90% of the peak response a frequency increment of 0.032 times the lowest frequency of interest is required and 114 logarithmic intervals are required for analysis between 5 Hz and 200 Hz (see Appendix).

Random Vibration

Random Vibration analysis is performed using Rigid Formats 8 or 11 as an extension of the frequency response analysis. One must run the frequency response analysis to get the random response analysis. The only additional requirement is the inclusion of the power spectral density (g^2/Hz) loading description, the TABRND1 card, which defines g^2/Hz versus frequency.

Shock

Shock analysis can be performed in NASTRAN but the uncertainty of the definition of the input makes the results questionable. The shock level is described as a shock response spectrum which is a shock response level (response g's) as a function of frequency. In order to perform a shock analysis, this shock response spectrum must be converted to a transient pulse. The problem is that a given shock response spectrum does not correspond to a unique transient input pulse. There could be several different types of transients that give the same shock response spectrum. If one does convert the shock response spectrum to a transient pulse, either the direct transient response, Rigid Format 9, or the modal transient response, Rigid Format 12, can be used for the analysis.

The transmission of a shock pulse through a structure is susceptible to the number of joints and the fixity of these joints in the path of the pulse. This characteristic is difficult to model. Therefore, caution should be used when interpreting the results of a shock analysis.

TEST LEVEL DEVELOPMENT

The paths for test level development for instruments or components can proceed in several different directions. Three examples will be given. The first is a review of methods employed for the development of levels for the components on the presently orbiting International Ultraviolet Explorer (IUE) spacecraft. The second is a description of the development of the test levels for components of the Tandberg-Hanssen instrument. This is an instrument that will be flown on the Solar Maximum Mission (SMM) spacecraft during 1979. The third is the development of test levels for the Thematic Mapper instrument. This instrument will be part of the LANDSAT-D mission and is scheduled for launch in 1981. The three situations are different as will be explained.

IUE Components

The system test levels for the IUE spacecraft (reference 1) were defined and known. Based on this information, test levels for the components were developed for sinusoidal vibration, random vibration, acoustic noise, shock, and steady state acceleration (reference 2). Since the input to the spacecraft was known, the problem became one of determining the response of the spacecraft at various locations which would describe the environment seen by a component mounted at that location. A graphical representation of the IUE spacecraft is shown in figure 2 and the NASTRAN models are shown in figures 3 and 4. For steady state acceleration and acoustic noise the levels for the components are the same as the levels for the spacecraft. For the other environments the levels for the components are dependent upon the dynamic response of the spacecraft.

The IUE Project was fortunate in that a structural model of the spacecraft was available very early in the program for testing. Consequently, the component test levels for sinusoidal vibration, random vibration, and shock were derived directly from test data. However, before the testing started, frequency response runs were made with the NASTRAN model to provide predictions of the responses at particular locations. These predictions agreed well with the test data. Although the NASTRAN model of the IUE spacecraft was not used to develop component test levels, it was used extensively in performing coupled launch vehicle/spacecraft launch loads analyses and also to predict occurrences during the sinusoidal vibration test of the spacecraft.

The technique for developing the sinusoidal vibration test levels for instruments or components is fairly straightforward. The method is to envelop the peak responses into a smooth spectrum as shown in figure 5. The same applies for shock response spectrum test levels as shown in figure 6.

The random vibration test levels were also developed from test data. However, one should not use the method of enveloping the peak responses because this results in a subsystem test specification that is much more severe than it should be. For the IUE components, the test data were divided into appropriate groups and a statistical analysis (reference 3) was performed to establish the random vibration specification for each group. More refined methods (reference 4 and reference 5) also consider the damaging effects of the environment when developing the subsystem test levels.

Tandberg-Hanssen Components

The test levels for the Tandberg-Hanssen instrument were established (reference 6) and two NASTRAN models of the instrument were generated. One was a small simple 400 degree of freedom beam model and the other was a very detailed 4000 degree of freedom model. The small model is shown in figure 7 and the large model in figure 8. The main purpose of the small model was to provide the SMM Project with an adequate dynamic representation of the instrument to be used in the coupled launch vehicle/spacecraft launch loads analysis. The large model was used to develop sinusoidal and random vibration test levels for selected components and also to examine critical loads for both the static and dynamic environments.

The sinusoidal vibration levels for one component, the polarimeter, were developed by first using the NASTRAN modal frequency response analysis. The model was excited in each axis according to the input levels described for the instrument (reference 6) and response plots were made at a point corresponding to the mounting location of the polarimeter. The response plots representing the thrust direction were examined as well as the response plots representing the lateral directions. The peaks of the responses were enveloped to develop a corresponding thrust axis specification and a corresponding lateral axis specification.

A critical component in the instrument is the circular flex pivot. The secondary mirror/two axis gimbal assembly is supported by four of these pivots and the pivots are particularly susceptible to failure due to random vibration. Even the large model did not have the flex pivot - secondary mirror/two axis gimbal assembly modelled. Therefore, the plan was to run a random response analysis using the large model and pick a response point that would represent the input to the secondary mirror/two axis gimbal assembly. Then, using the calculated response, a random vibration specification would be generated for the secondary mirror and gimbal assembly. The analysis was run, the responses were plotted, and the random vibration specification was determined using the methods previously cited (reference 4).

Development of a random vibration specification, whether it be from test data or from analytical predictions, is a subjective procedure. The more refined methods (reference 4 and reference 5) are a step in the direction of removing some of the subjectiveness. However, even these methods are not universally accepted. Without going through the refined techniques, a suggested method is to manually smooth out the response so that the reuslting specification has an overall level that is no more than approximately two times the overall level of the response. An example of this technique is shown in figure 9.

Thematic Mapper

The Thematic Mapper is a large and complex earth viewing instrument that will be flown on the LANDSAT-D spacecraft. Because it represents an advanced long-lead time item, the instrument is being designed and built prior to the spacecraft. Consequently, the test and design levels for the instrument have had to be developed before the dynamic characteristics of the spacecraft become known. Also, the test levels have been made compatible with both the launch environment of the Delta launch vehicle and the launch and recovery environments of the Space Shuttle. The test levels developed for the Thematic Mapper are sinusoidal vibration, random vibration, shock, acoustic noise, and steady state acceleration.

The steady state acceleration levels used for the Thematic Mapper covered Delta launch (reference 1) and Shuttle launch, landing, and crash (reference 7 and reference 8). The acoustic noise specification was based on the worst case combination of the Delta and Shuttle environment. The predicted acoustic environment for the Shuttle below 200 Hz is significantly higher than the environments of any of the expendable launch vehicles. To cover this condition, a low frequency random vibration test was specified from 20 Hz to 200 Hz. The determination of the random vibration levels was based on a procedure outlined for Shuttle payloads (reference 8). This procedure requires knowledge of the mass distribution of the payload from which reaction loads are calculated. For the Thematic Mapper the payload is the LANDSAT-D spacecraft mounted in a cradle. Since this information was not known, some assumptions were made which would yield a worst case condition and the random vibration levels were derived from this condition. The shock levels were based on the recommendations for component vibration (reference 1).

The sinusoidal vibration levels were derived using a NASTRAN model of a "characterized" LANDSAT-D spacecraft. Since, as indicated, the LANDSAT-D spacecraft has yet to be designed, the NASTRAN model was based on conceptual design information. Also, stiffness parameters for the conceptualized spacecraft and the instrument support module were varied to try to bound the best and worst case conditions that could be expected from the final design. The NASTRAN model used in the analysis was a simple beam and is shown in figure 10. The frequency range of the analysis was from 5 Hz to 100 Hz and the beam representation was considered satisfactory for the analysis.

Two types of analyses were performed using the beam model. One was a modal transient response of the combined spacecraft and Delta launch vehicle. This was used in the simulation of the lateral liftoff event. The output from this analysis was the acceleration levels at all the indicated points on the LANDSAT-D spacecraft model and also the bending moment at the Delta attach fitting/spacecraft interface. The bending moment was of interest because it is the load that is traditionally used as a limitng factor during lateral sinusoidal vibration tests of spacecraft.

Using the bending moment predicted from the lateral liftoff analysis as a limiting factor, a frequency response analysis was run which simulated the lateral sinusoidal vibration test of the spacecraaft. A modal Q of 15 was assumed and the predicted response at the mounting location of the Thematic Mapper was output. The responses indicated that the Thematic Mapper would be exposed to levels during the spacecraft lateral sinusoidal vibration test that would be higher than the levels predicted to occur due to the liftoff event. Therefore, in order not to overtest the instrument, it was decided to base the lateral sinusoidal levels on the responses predicted from the lateral liftoff analysis. This, in turn, will probably impose some restrictions during the lateral sinusoidal vibration test of the total spacecraft system to ensure that overtesting of the instrument does not occur.

For the Delta launch vehicle the maximum thrust axis dynamic response occurs as a result of POGO. POGO is a longitudinal oscillation resulting from closed-loop coupling of the engine system and the vehicle longitudinal mode and is the major thrust axis dynamic loading. A thrust axis frequency response analysis simulating the thrust axis vibration test of the spacecraft was run. The predicted response at the mounting location of the Thematic Mapper resulting from the POGO event was used as the maximum thrust axis sinusoidal vibration test level for the instrument.

As can be seen, sinusoidal vibration levels for the Thematic Mapper were derived from predicted responses due to launch events. This departs from the traditional approach which required instruments or components to survive not only the levels predicted for flight but also the levels that would occur during sinusoidal vibration testing of the spacecraft to which the instrument was mounted. This often times resulted in considerable overtesting and overdesign of instruments. The approach used for developing the sinusoidal test levels for the Thematic Mapper does not contradict existing test philosophy but it does impose restrictions on spacecraft testing to ensure that instruments and components are not overtested.

CONCLUDING REMARKS

The three examples given demonstrate variations in the development of test levels for instruments and components. For the IUE components, the test levels were developed primarily from test data. For the Tandberg-Hanssen instrument, the levels were defined and the instrument component levels were derived from analysis. For the Thematic Mapper instrument, the levels were developed based on launch environment analysis, statistical information, and mutual spacecraft environments such as steady state acceleration and acoustic noise. Of the three, the preferred approach is that used for the Thematic Mapper instrument. This approach provides the levels that are the most consistent with the occurrences due to the launch.

The analyst must determine the environment that is most critical for the instrument and therefore the priority to place in the analysis plan. The first priority should be the steady state acceleration analysis because this is the environment that generally produces the highest load on the primary structure of the instrument. The next step should be the sinusoidal vibration analysis. This analysis frequently indicates high dynamic loads on some parts of the instrument. If this is the case, one should pursue the possibility of doing a launch loads analysis to determine if the loads predicted from the sinusoidal vibration analysis are realistic. However, typically a launch loads analysis is not a readily available option. Therefore, one should keep in mind that response levels on the order of 20 g's, assuming a modal Q of 15, probably will not be exceeded during launch. Some engineering judgment should be exercised before making design changes because of high loads predicted from sinusoidal vibration analysis. The random vibration analysis is one that should not be overlooked. Generally, random vibration is a high frequency environment that causes problems with electronic components or boards and also picks up workmanship problems. However, there are times when random vibration does cause structural problems. The analyst will have to use his own judgment when determining whether or not a random vibration analysis is warranted. The analytical shock analysis is questionable because the response is dependent upon the input and the definition of the input is not unique. Acoustic noise analysis is not done as a matter of course basically because the analytical definition of the input is difficult and the analysis is too complex to spend the time to do it. If an instrument is designed to withstand steady state acceleration loads, sinusoidal vibration loads, and random vibration loads the chances are that a failure will not occur due to shock or acoustic noise.

REFERENCES

1. General Environmental Test Specification for Spacecraft and Components (Expendable Launch Vehicles). GETS(ELV)-1, NASA/Goddard Space Flight Center, May, 1977.

2. Environmental Test Specification for IUE Subsystems. IUE-320-74-008 Revision 1, NASA/Goddard Space Flight Center, December, 1975.

3. Keegan, W. Brian: A Statistical Approach to Establishing Subsystem Environmental Test Specifications. X-321-74-174, NASA/Goddard Space Flight Center, June, 1974.

4. Stahle, C. W.; and Gongloff, H. R.: Interim Report Study on Component Environmental Specification Development and Test Techniques. G. E. Document No. 75SDS4254, General Electric Space Systems Organization, October, 1975.

5. Keegan, W. B.; Stahle, C. E.; and Gongloff, H. R.: Development of Component Random Vibration Requirements Considering Response Spectra. The Shock and Vibration Bulletin, The Shock and Vibration Information Center, August, 1976.

6. SMM/Experiment General Interface Specification. SMM-670-01 Revision 1, NASA/Goddard Space Flight Center, September, 1976.

7. Space Shuttle System Payload Accomodations. JSC 07700 Volume XIV Revision E, NASA/Lyndon B. Johnson Space Center, June, 1977.

8. Shuttle Orbiter/Cargo Standard Interfaces. ICD No. 2-19001, NASA/Lyndon B. Johnson Space Center, October, 1977.

APPENDIX

Determination of the minimum number of points required for a frequency response analysis to assure that the calculated response is at least 90% of the peak response.

Nomenclature

f	-	frequency
f_H	-	high root of equation
f_L	-	low root of equation
f_n	-	natural frequency
HF	-	high frequency
LF	-	low frequency
N	-	number of points
Q	-	modal amplification
X_I	-	imaginary response
X_R	-	real response
Δf_{max}	-	maximum increment; $(f_H - f_L)\, f_n$

Assume a single degree of freedom system

$$X_R = \frac{1-\left(\frac{f}{f_n}\right)^2}{\left[1-\left(\frac{f}{f_n}\right)^2\right]^2 + \left(\frac{f}{Qf_n}\right)^2} \quad \text{and} \quad X_I = \frac{-\frac{f}{Qf_n}}{\left[1-\left(\frac{f}{f_n}\right)^2\right]^2 + \left(\frac{f}{Qf_n}\right)^2}$$

let $f_n = 1$ then

$$X_R = \frac{1-f^2}{(1-f^2)^2 + \left(\frac{f}{Q}\right)^2} \quad \text{and} \quad X_I = \frac{-\frac{f}{Q}}{(1-f^2)^2 + \left(\frac{f}{Q}\right)^2}$$

$$\text{Response Magnitude} = \sqrt{X_R^2 + X_I^2}$$

$$= \frac{1}{\sqrt{(1-f^2)^2 + \left(\frac{f}{Q}\right)^2}}$$

for $f=1$ Response Magnitude = Q

Let Response Magnitude = 0.9Q

then

$$0.9Q = \frac{1}{\sqrt{(1-f^2)^2 + \left(\frac{f}{Q}\right)^2}}$$

and

$$f^4 - \left(2 - \frac{1}{Q^2}\right)f^2 + 1 - \frac{1}{0.81Q^2} = 0$$

from the equation above

Q	f_L	f_H	f_H/f_L	$f_H - f_L$
5	.939	1.039	1.106	.100
10	.973	1.022	1.050	.049
15	.983	1.015	1.033	.032
20	.987	1.011	1.024	.024

A. For a logarithmic sweep

$$N = \frac{\log\left(\frac{HF}{LF}\right)}{\log\left(\frac{f_H}{f_L}\right)}$$

B. For a linear sweep

$$\Delta f_{max} = (f_H - f_L)\ f_n$$

Figure 1.
TYPICAL ENVIRONMENTAL TEST AND ANALYSIS PLAN

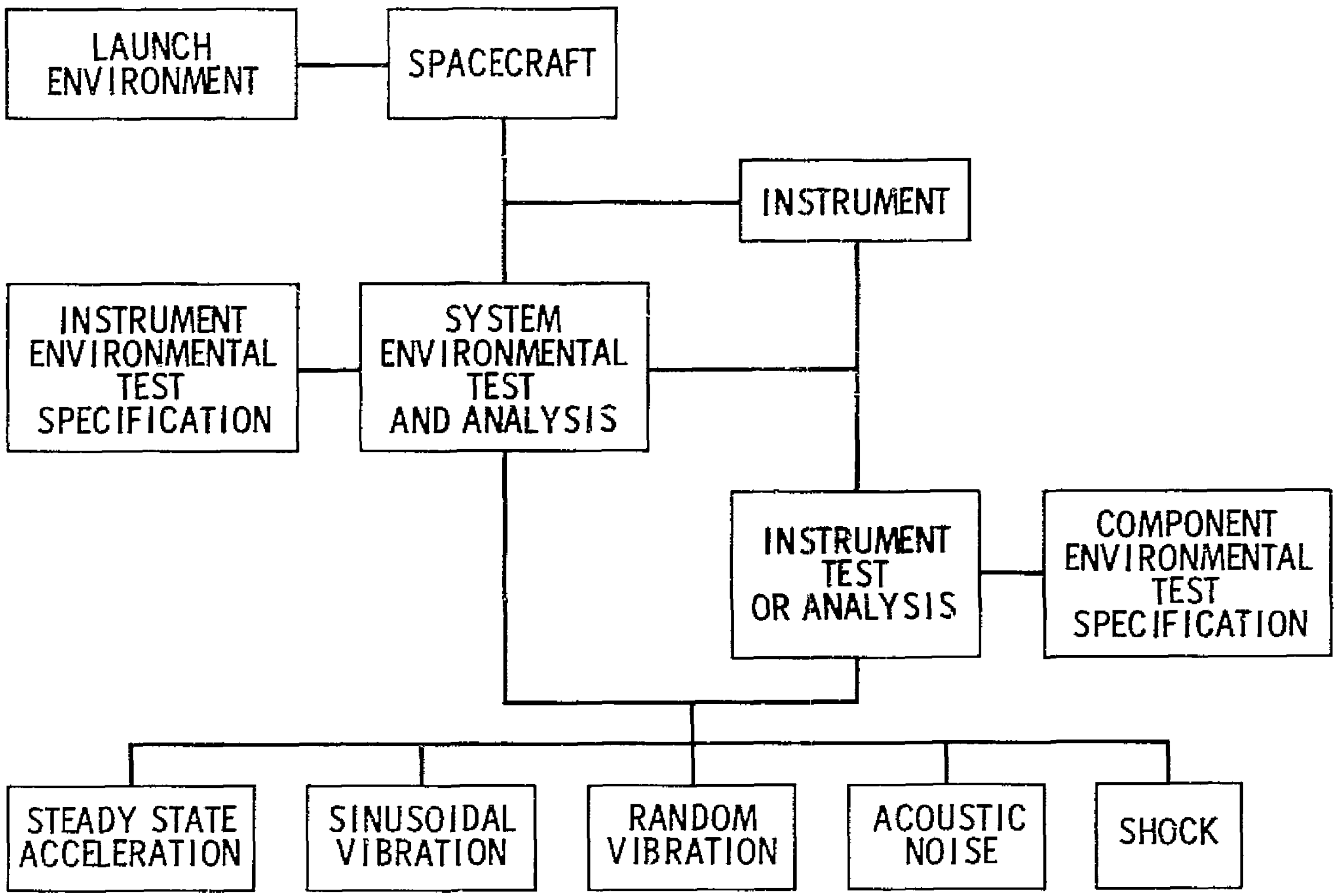

Figure 2.
IUE EXPLODED VIEW

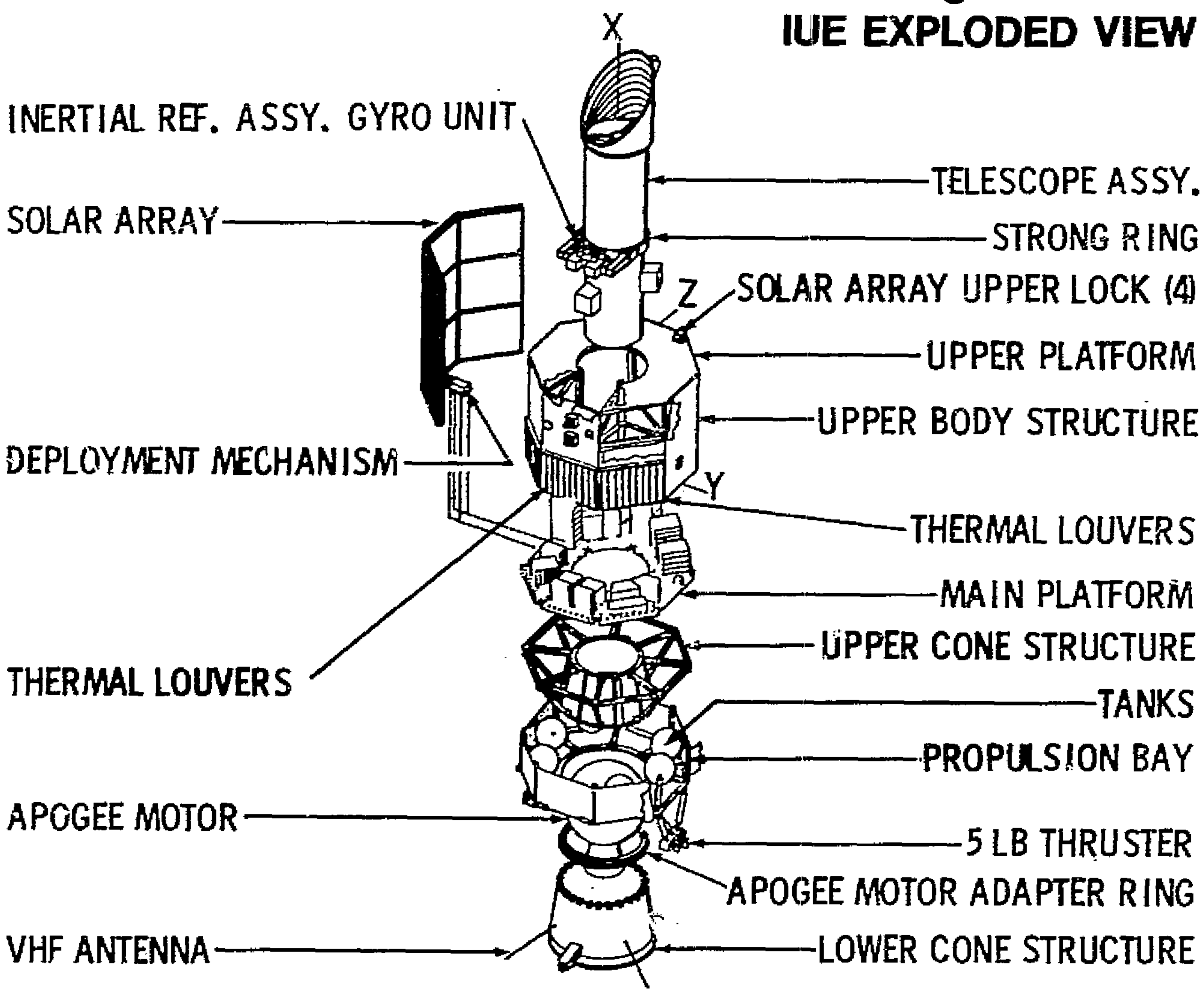

Figure 3.
FINITE ELEMENT MODEL OF IUE SPACECRAFT STRUCTURE

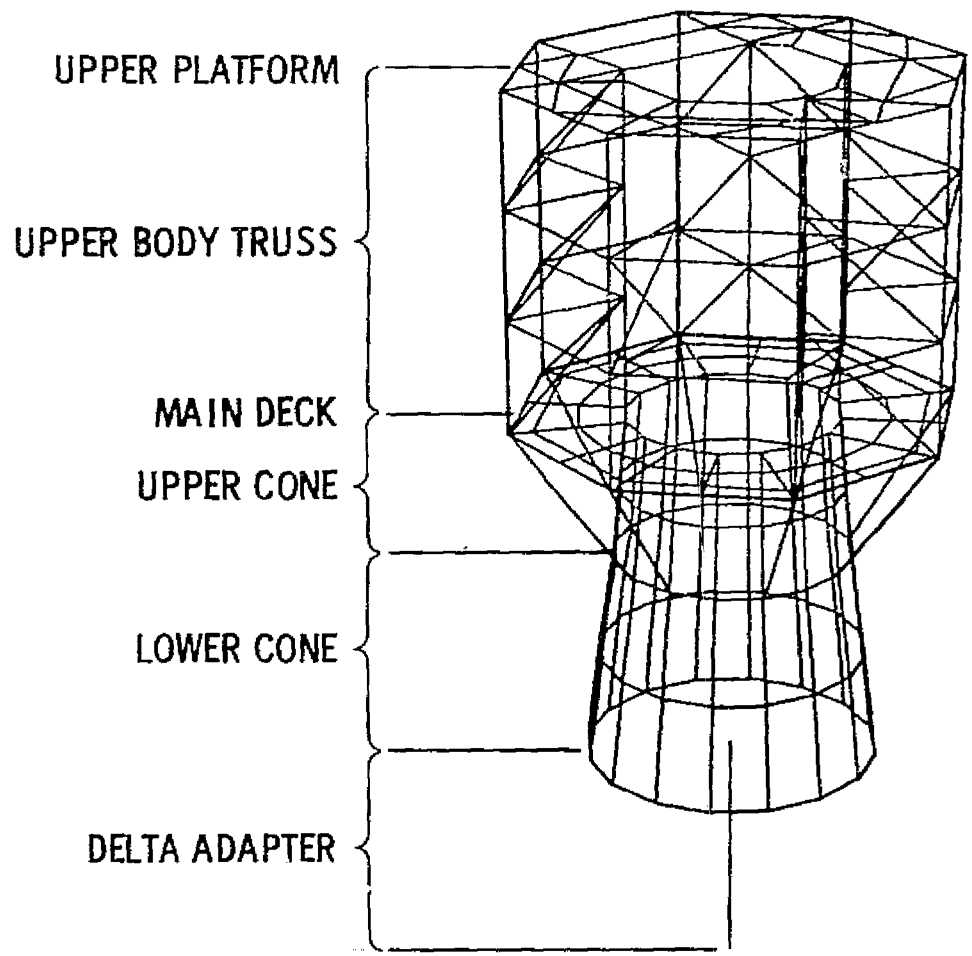

Figure 4.
FINITE ELEMENT MODEL OF IUE SCIENTIFIC INSTRUMENT

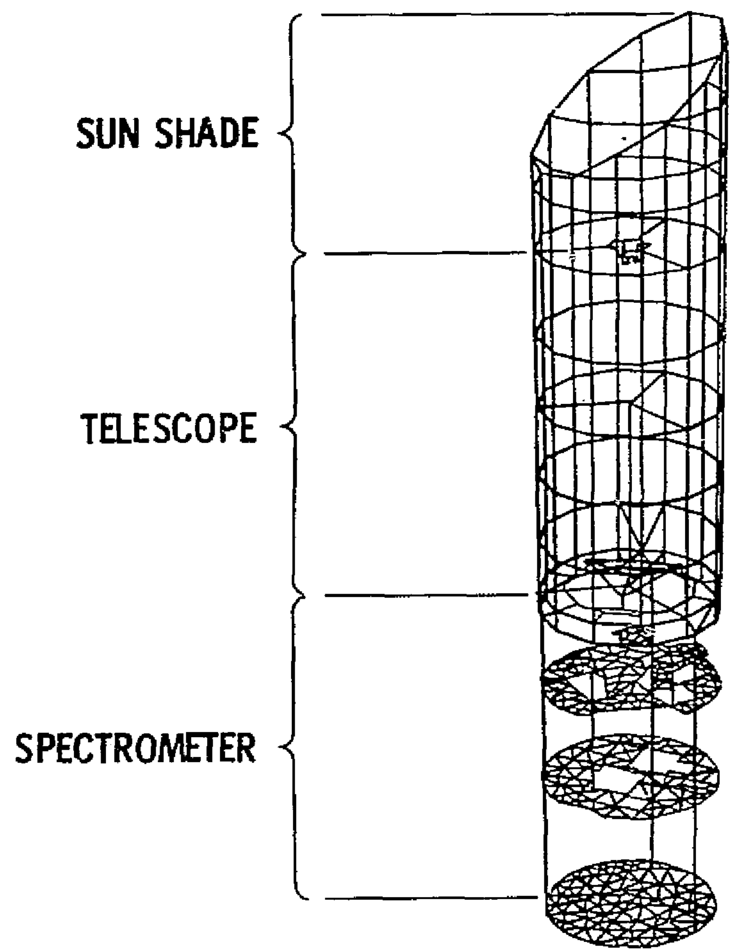

Figure 5.
EXAMPLE OF SINUSOIDAL SPECIFICATION

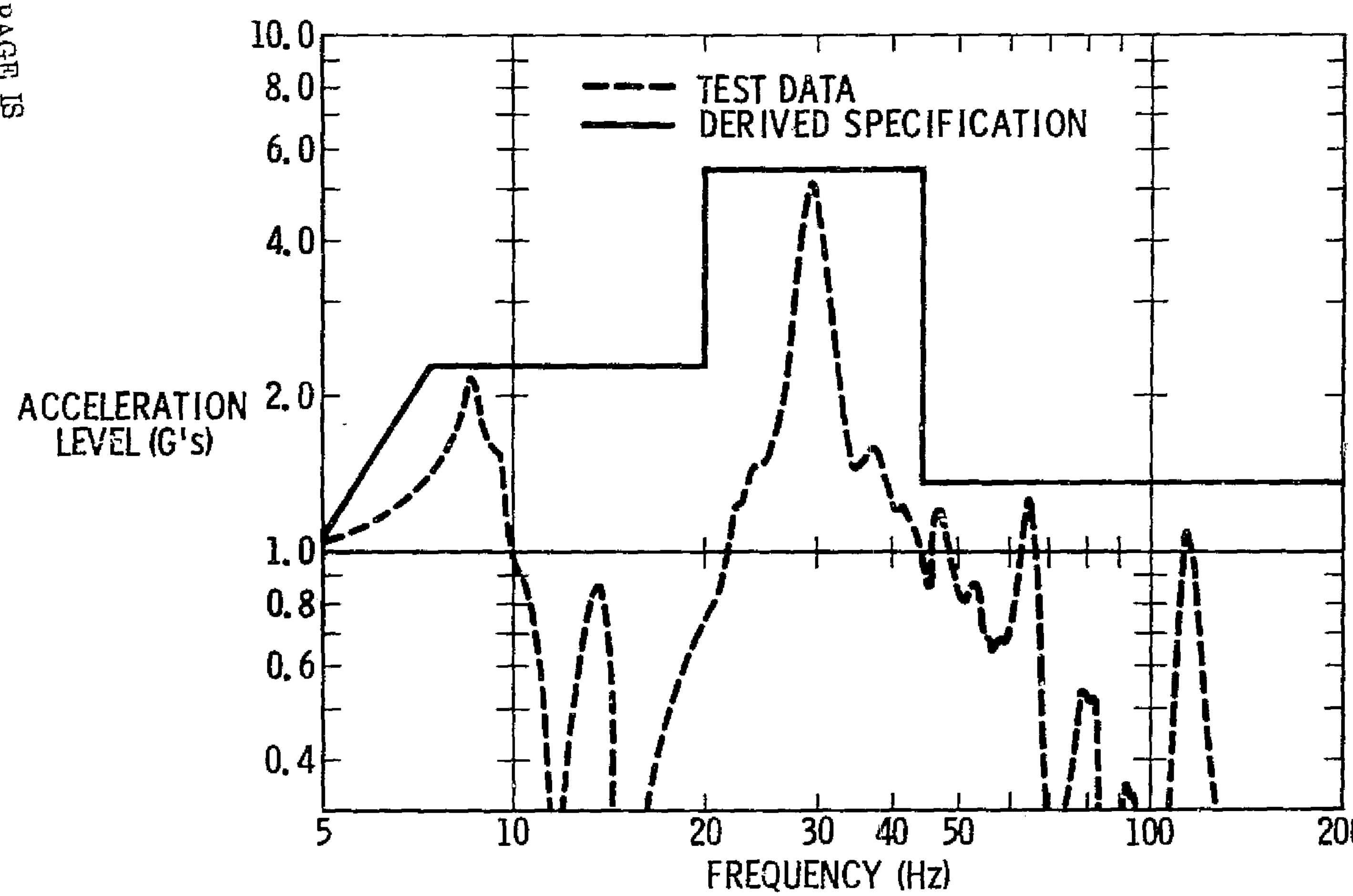

Figure 6.

EXAMPLE OF SHOCK RESPONSE SPECTRUM SPECIFICATION

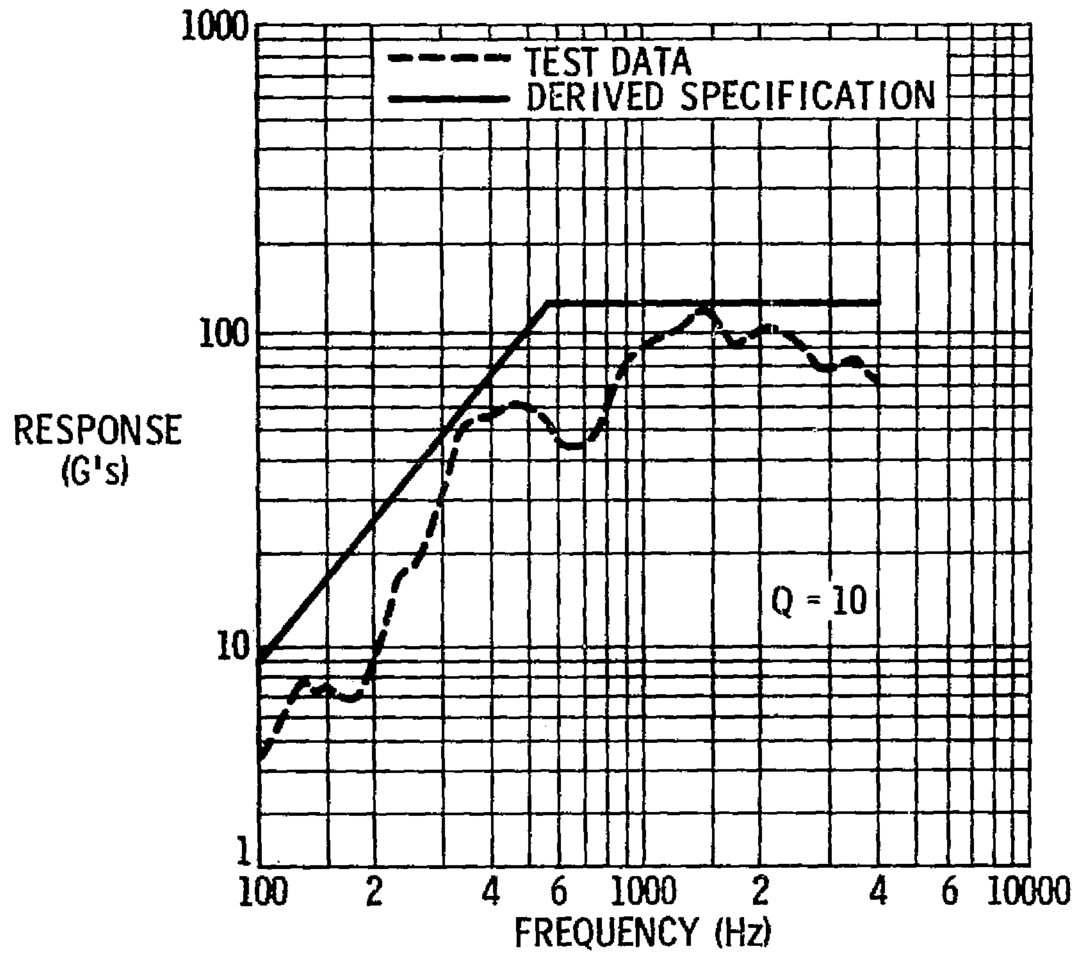

Figure 7.
TANDBERG HANSSEN SIMPLE BEAM MODEL

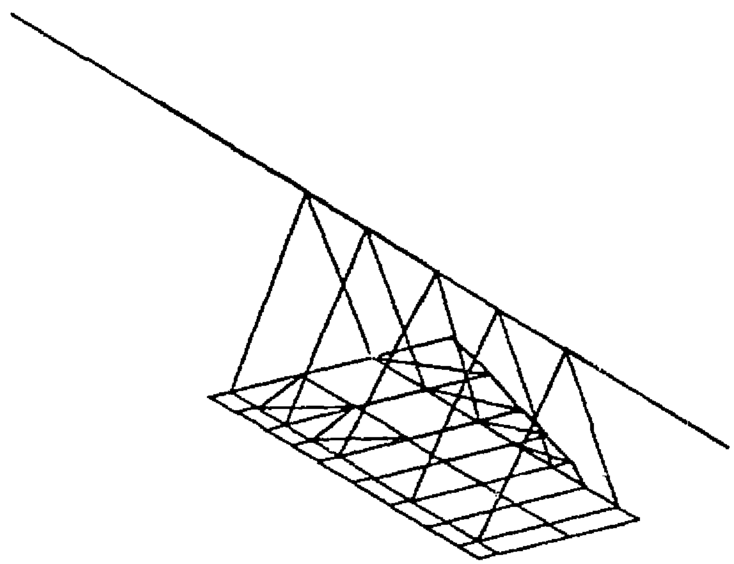

Figure 8.
TANDBERG HANSSEN DETAILED MODEL

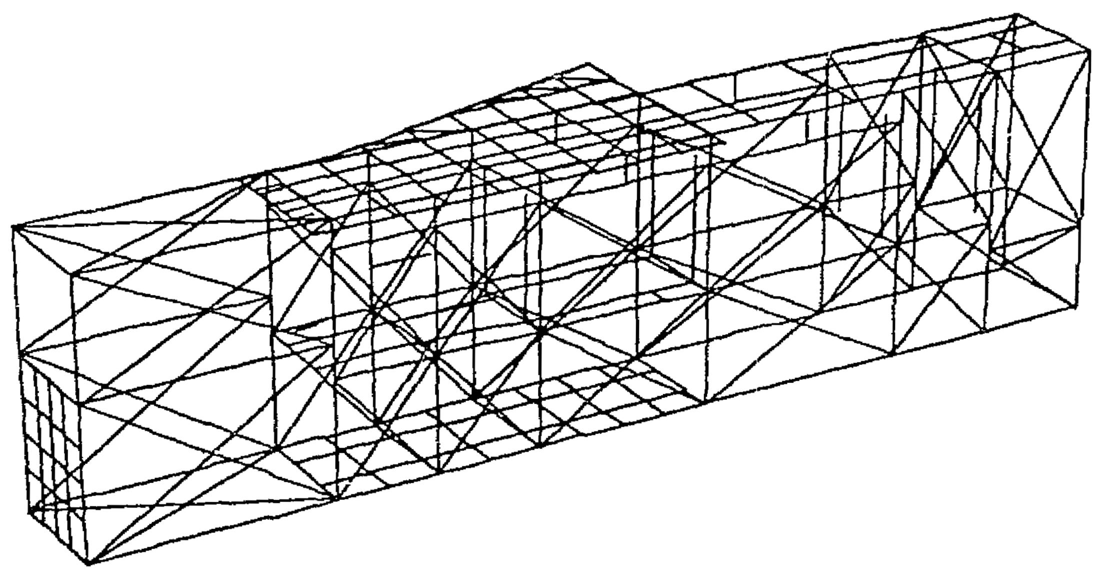

Figure 9.
EXAMPLE OF RANDOM VIBRATION SPECIFICATION

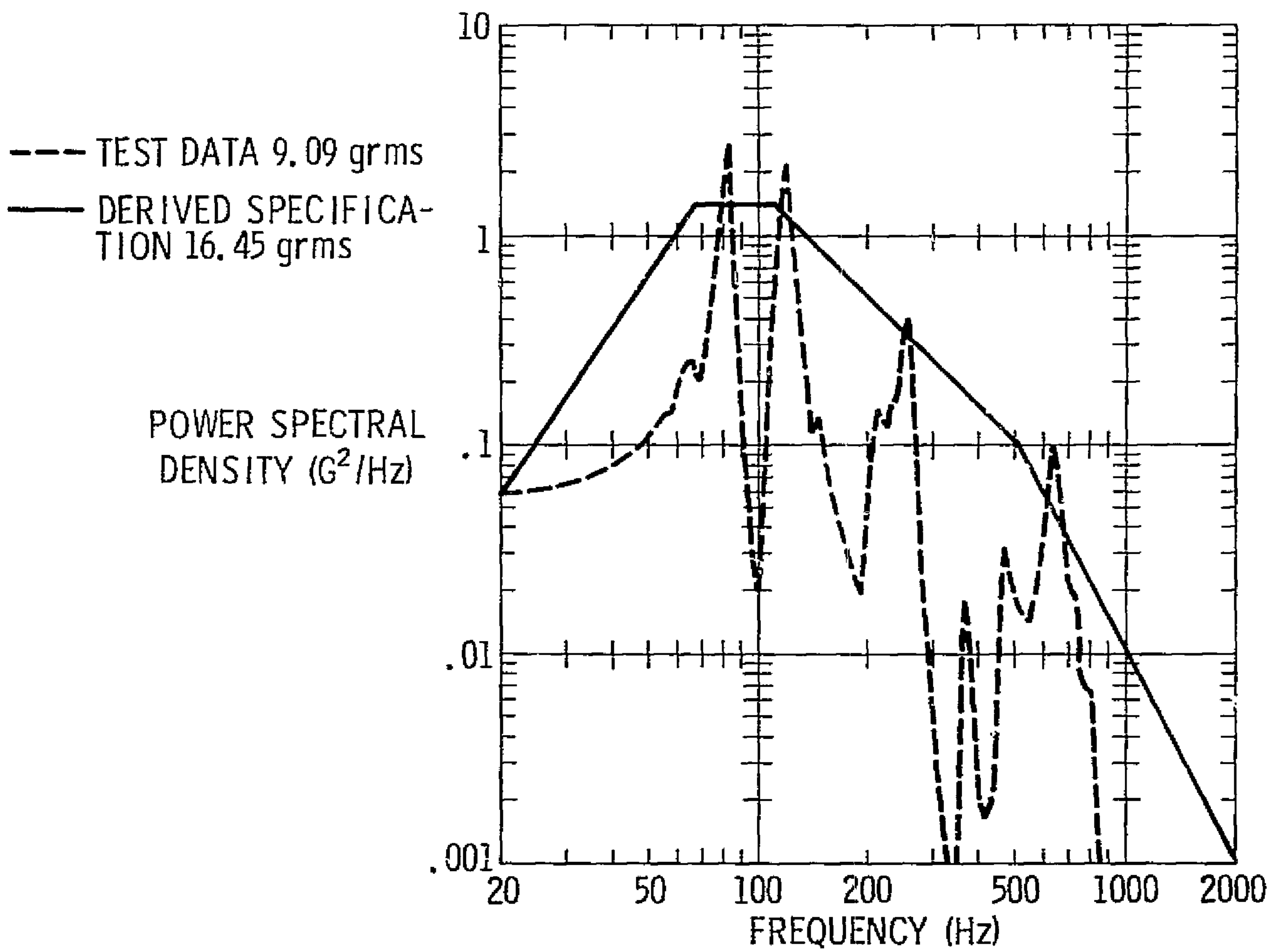

Figure 10.
LANDSAT-D SIMPLE BEAM MODEL