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SEVERE SHOCK AND VIBRATION ENVIRONMENTS FOR ELECTRONIC COMPONENTS*

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ABSTRACT

Electronic components used in system applications must be qualified to mechanical shock and vibration environments. Often these environments are severe, requiring the development and use of special test techniques and procedures. Environmental specifications are based upon analytical model predictions and measured test data. Test specifications are determined after careful consideration of simulation techniques, input levels, dynamic behavior of the test fixturing, as well as an assessment of the degree of conservatism imposed by the specification and testing procedures.

The process of determining component shock and vibration specifications is discussed, beginning with the initial description of system and subsystem level environments, and concluding with the component level test specifications. Included is a discussion of the difference between environmental specifications and test specifications, and the instrumentation/measurement problems associated with obtaining valid field measurements for severe shock data. The role of finite element analysis in predicting the dynamic structural response of components is also explained. Shock data analysis techniques are described including both time-domain and frequency-domain characterizations of the data. The resonant plate shock testing technique for simulating severe shock environments is presented, including difficulties that arise in practical applications.

I. INTRODUCTION

Electronic components used in system applications must be designed to survive mechanical environments. Often the most severe environments are shock and vibration. The design requirements are determined based on a combination of analysis, laboratory testing, and field test data. In some applications, the environment is defined as input to a system or subsystem. That environment must be transferred to the component level either by test or analysis. Current techniques utilize finite element modeling and analysis to calculate the dynamic response of the system. Both models and test data are necessary to adequately verify the design.

In this paper, an example of a re-entry vehicle is used to describe the component qualification procedure. The vehicle consists of an aeroshell plus internal subsystems, one of which is an electronic package containing components mounted in rigid foam. The ultimate goal is to define the specifications for the components inside the electronics package. Figure 1 depicts the specification process, showing the supporting test activities, the major structural and data analysis activities, and key documentation.

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DISCLAIMER

The document path begins with the STS, which defines system level environments, of which the mechanical environments are only a part. The SB and CD documents extract the appropriate information from the STS to define the subsystem or component environments that are applicable to specific hardware. The PS (product specification) defines the component test specifications, which are transmitted to the production and testing agencies.

Finite element modeling and analysis is necessary to predict component responses for which field test simulation is not possible. The testing activities require interaction between measurement personnel, structural analysts, and test engineers to ensure meaningful tests and data are obtained. Instrumentation and data analysis are required to generate a data base from which the component specifications can be determined. The specification process requires both time domain and frequency domain descriptions of the data.

This paper addresses both environmental specifications and test specifications. These activities require an integration of finite element analysis, testing, and data analysis. The specification process requires technical support in several areas including modeling, loads definition, test/analysis correlation, digital signal processing, environmental data analysis, as well as the test specifications.

II. ENVIRONMENTAL SPECIFICATIONS VS. TESTING SPECIFICATIONS

Environmental data analysis involves the study of measured field data. The data must be characterized, evaluated, and summarized. This typically involves enveloping the data in a way that is both tractable and meaningful. Environmental specifications should describe the input environment, both in terms of time domain and frequency domain information.

Test specifications should describe the simulation technique and inputs to be used, and should also include descriptions of test fixtures, instrumentation, and input control techniques. There are often several alternative test techniques that are available for simulating a desired environment. The selection should be made after carefully considering test conservatism, test realism, and implementation practicalities. There must also be constant evaluation to ensure that component level testing produces an environment that is representative of the system level field environment.

Transient dynamic environments can be separated into three categories: sine vibration, random vibration, and shock. Random vibration and transient shock are the two most common environments experienced by electronic components in applications. Component specifications are based on acceleration data. Both time and frequency domain properties are utilized.

Sine and random vibration are typically described in the frequency domain. Sine vibration is defined in terms of amplitude or peak-g vs. frequency. Random vibration is defined in terms of the autospectral density or power spectral density (PSD) (1). The PSD is a density plot of the energy (or power) as a function of frequency. Figures 2a-b show a random vibration time history and its associated PSD.

Shock data are defined in both the time and frequency domains. The frequency domain description consists of the shock spectrum (2) and the Fourier spectrum. Component test specifications are given in terms of the acceleration shock spectrum, although the acceleration-time histories are also critically important when defining the shock environment. The shock spectrum is a function that depicts the damage potential of the input shock as a function of frequency. Figures 3a-b show a time history and its associated shock spectrum.

Shock spectra and PSD's from several individual field tests and model predictions are typically enveloped to determine appropriate environmental specifications. Then a test specification is determined based upon the enveloped field data. There is conservatism introduced into the environmental specifications simply due to enveloping several individual events. Additional conservatism may be introduced into the test specifications to account for limitations in test techniques. Figures 4a-b show a shock spectrum environmental specification and its associated test specification (superimposed on the environmental envelope).

The determination of an appropriate component environmental and test specification is a complicated process. It can be successfully accomplished only if the proper environmental description is available. If the environmental specification does not include a complete description of the input, (including time domain information for shock), it is impossible to develop a realistic test specification. Often, this is the case; i.e., the environmental specification is really an incompletely defined test specification in which a particular test technique has already been assumed. When this occurs, the results are poor simulations of the environments, severe over tests, and insufficient information to make technical decisions in the event of test induced failures.

III. TIME AND FREQUENCY DOMAIN DESCRIPTION OF SHOCK AND VIBRATION DATA

The PSD is a real-valued function that establishes the frequency composition and statistical properties of random vibration data. In practice, it is calculated by sampling the time history data and using discrete Fourier transforms (3). The PSD is related to the magnitude squared of the Fourier transform. The time domain description of random data consists primarily of the peak amplitude (i.e., the three-four sigma peaks) and time dependency of those peaks (i.e., stationarity). The mean square (statistical property) of the time-domain data is equal to the integral under the PSD curve. The square root of the mean square is equal to the rms (root mean square) amplitude. For Gaussian data, the rms is equal to the one-sigma level, and 99.7% of the peaks fall within the plus and minus three sigma levels.

These relationships can be seen in Figure 2. A visual inspection of the time history indicates the peak acceleration (peak-g) levels in Figure 2a are approximately 24 g - 30 g. The g-rms as calculated from Figure 2b is 7.5 g-rms. Other statistical tests can be performed to determine how close to Gaussian these data actually are. If the data in Figure 2 were Gaussian, the three-four sigma peaks should be 22.5 g - 30 g, which is very close to the measured peaks in the time history.

The shock spectrum is widely used in the aerospace industry. It is a frequency domain plot showing the maximum response of a single-degree-of-freedom (SDOF) system to the input time history. This maximum is plotted as a function of the resonant frequency of the SDOF system. Figure 5 depicts an example of this calculation. The shock spectrum is an indication of the damage potential of the pulse. The time domain description of shock data includes the peak-g levels, decay rate, and oscillatory nature of the pulse. Note that there is a difference in the peak accelerations in the time history and shock spectrum. This is often a point of confusion.

Figure 3 shows typical differences that can be expected in actual field data. The peak acceleration in the time domain is approximately 1500 g's. The peak-g in the shock spectrum is over 7000 g's. The ratio of peak-g in the shock spectrum to peak-g in the time history is a function of the decay rate of the time history. For a one-sided, single pulse (i.e., haversine or half sine), this ratio is approximately 1.7; however, for a highly oscillatory pulse the ratio is typically between three and ten.

There are several parameters that must be selected when computing the shock spectrum. Because the calculation is for a SDOF system, many response quantities can be computed, including: peak acceleration, velocity, or displacement (strain, etc.); relative or absolute response; peak positive or peak negative response; and peak response either during the time of the input pulse duration or after the pulse has died out (referred to as the residual response). The most common application for component specifications is the maximum of all absolute accelerations. This is referred to as the maxi-max absolute acceleration shock spectrum.

The shock spectrum is only an indirect measure of frequency content of the pulse. It should not be confused with the Fourier transform, which is a direct measure of the frequency content. In fact, when the shock spectrum approaches a constant (above 15,000 Hz in Figure 4b), there is no more frequency content in the input pulse; whereas, the Fourier transform of the input would go to zero above this frequency. For the acceleration shock spectrum, this simply means that a SDOF system will track the input one-to-one at frequencies that are high with respect to the frequencies in the input pulse.

The shock time history contains very important information needed to define the environment. Although the official shock specifications for components may be given only in terms of shock spectra, the time history characteristics should also be directly or indirectly simulated so that realistic test specification can be developed.

IV. SHOCK AND VIBRATION TEST SIMULATION TECHNIQUES

Sine and random vibration tests are input using shake tables. These are either electrodynamic or electrohydraulic machines with large power amplifiers driving the vibration exciter. Shock test simulation currently consists of three techniques: drop table methods, resonant plate methods, and digital transient shake table methods.

Drop table methods produce simple, one-sided pulses (i.e., haversine or half sine), which typically have a large velocity change. Resonant plate and transient shake table tests both can produce double sided, exponentially decaying inputs, typically with little velocity change. The test technique should be selected to simulate the field shock characteristics as closely as possible.

Shock environments experienced in current re-entry vehicle applications are more appropriately represented by decaying oscillatory pulses. Time history data up to 2000 g and between 5000 Hz - 10,000 Hz are common for the most severe events. Environments experienced in lay-down bomb applications comprise both one-sided and oscillatory shocks. The oscillatory pulses have peak g-levels and frequencies similar to the re-entry vehicle data. The one-sided pulses are typically below 2000 Hz, with g-levels up to 2500 g's, and with associated velocity changes up to 130 ft/sec (39.5 m/sec). Artillery shell launch environments are typically of very long duration. They are single sided pulses with amplitudes up to 15,000 g's and durations of up to 15 milliseconds. These are often treated as steady state loads due to their long durations and lack of test facilities to reproduce the large velocity changes.

Digital transient shock simulation is a versatile technique for performing shock tests. Decayed sinusoid pulse generation (4-5) is first used to obtain the desired acceleration time histories. Then, computer controlled electrodynamic or electrohydraulic vibration tables are used to input the shock. This technique has the capability to simulate both the time and frequency domain characteristics of the input field data. The only disadvantage is that shakers are currently limited to maximum frequencies of 2000 - 3000 Hz and maximum acceleration levels of 200 - 300 g's peak.

The newest development in shock testing is the resonant plate technique (6-7). Figure 6 shows the test setup. An air gun is typically used to launch a projectile that impacts the plate. The plate dimensions are chosen so that the first plate bending mode frequency is tuned to the frequency at which most of the input energy exists in the field data. (Higher harmonics of the plate are also excited.) The component is then mounted to the plate. The projectile impacts the plate, exciting the plate motion, which in turn imparts base excited motion to the component. Bars are attached (clamped) to the sides of the plate, introducing a vibration suppression mechanism to control the decay rate of the pulse. This technique is now used to simulate oscillatory pulses with amplitudes between 500 g - 5000 g, and frequencies between 250 Hz - 10,000 Hz.

There are important differences in the shake table and resonant plate test techniques. In resonant plate testing, it is difficult to directly control both the peak g-level in the time domain and the shock spectrum. If both are specified as inputs, a doubly defined test results. However, both of these parameters can be directly specified in the shaker testing due to the test technique and digital computer control. For most system applications, both types of oscillatory shock test simulations are required.

V. MODELING AND ANALYSIS

Modern engineering analysis utilizes finite element techniques to predict the dynamic response of structures. For the re-entry vehicle, both system level and subsystem level models were developed and verified using component mode synthesis (8-10), modal testing, and system identification techniques (11-12). These techniques were tailored for applications to aeroshells and electronic packages. The models were used for dynamic analysis, design evaluation, test support, and test/analysis correlation. The finite element analyses complemented the environmental data analysis, instrumentation, and testing. All these activities provided information required to develop the environmental and test specifications. Reference 13 discusses the modeling and analysis efforts.

Mechanical design loads were separated into normal and hostile environments. Two models were developed; one for hostile loads calculations and one for normal loads. The hostile environments are induced by impulse, blast, or in-depth heating loads. The hostile model was tailored to predict the shock response of the electronic components. This requires accurate prediction of both the amplitude and frequency content of the acceleration response. Test/analysis shock spectra correlations showed very good results (13).

The normal loads are caused by transportation and flight environments. The transportation loads consist of shock and vibration inputs from truck, air or rail transport, and handling. The flight loads are induced by the missile launch and re-entry events, and are defined as shock and vibration environments. They are based upon many flight test measurements obtained on previous re-entry vehicles. The flight environments are specified at a level associated with a 1-in-500 occurrence based upon flight data statistics (14).

VI. TESTING SUPPORT AND MEASUREMENTS

Both full-body and subsystem level testing is critical to the development of component specifications. Issues from several technical areas must be addressed including: 1) test and load simulation techniques, 2) test procedures, 3) boundary condition simulation, 4) transducer type, placement, and mounting schemes, 5) signal processing and frequency bandwidth requirements, 6) data analysis procedures, and 7) data validation. Clearly the measurement/instrumentation/data analysis support required for field testing has become complex. The critical task of validating field data requires a significant effort. Someone must be involved in all aspects of the process. Unless this support is given, the field data are useless, and environmental specifications are based on noise, not data.

Some of the component environments must be obtained by test due to the frequency ranges of the input loads. The testing program is critically important and complements the finite element modeling efforts. Current component specifications exist up to 4000 Hz in vibration and 10,000 Hz in shock.

Hostile loads are applied directly to the aeroshell surface of the re-entry vehicle. They are defined only at the system level. Separate system level tests were performed which simulated impulse, blast, and thermo-structural or in-depth heating loads. The component acceleration data obtained from these three hostile loads were directly used to develop the shock spectrum data base and the environmental specifications.

The hostile shock tests produce a very difficult environment in which to measure acceleration. The success of obtaining these data requires the integration of resources from testing, measurement, analysis, and project support. The system tests provided valid accelerometer data up to 10,000 Hz (see Figure 4). The quality of the measured data was extremely high but required special procedures be followed (15). These included a combination of 1) mechanical filtering of the transducers using soft-mounting techniques, 2) electrical filtering of the data, 3) dual recording to confirm that transducer output at the gage resonant frequency did not contaminate the structural response data, and 4) hardware modifications to install the gauges on small, non-rigid components. In addition, the qualification shock test procedures and fixturing to be used at the production agencies must be considered when determining the instrumentation and measurement requirements for the system level field tests.

Simulation testing for flight environments introduces difficulties. There are different boundary conditions in the ground test than exist in flight. Also the input may be applied to the structure through different loading mechanisms. For re-entry random vibration, the actual flight imposes free-free boundary conditions with an acoustically induced pressure loading on the surface of the vehicle. The launch staging shocks are induced through a flexible missile structure supporting the vehicle equipment section. However, the ground test consists of a fixture which interfaces to a very large shaker with a significantly different impedance than that of a missile equipment section or free-free flight conditions. These complications prevent ground testing from duplicating actual flight responses.

The goal is to select a conservative but realistic test. Often the input must be modified to account for the differences in boundary conditions. In system level ground tests, the focus is to tailor the test for specific internal component responses. An attempt is made to design the fixturing to be more stiff than the actual field conditions, and to modify the input levels and control techniques to compensate for any unnatural responses that are induced. A consequence of this is that the ground flight testing typically produces responses that exceed those seen in flight. This was true both for the system and subsystem level tests (13).

The electronics package shock and vibration testing included both evaluation and qualification testing. The evaluation tests consisted of sine and random vibration surveys, as well as detailed modal testing. The qualification tests provided data that were directly used to determine internal component specifications. However, a severe problem of boundary condition differences was encountered. The goal of the subsystem test was to simulate the electronics package response in the full system. However, the subsystem to shaker interface did not represent the true flexibility of the aeroshell. This complication required a modification to the test inputs in an attempt to better simulate the component responses in the system level flight tests. (13)

VII. MECHANICAL TEST SPECIFICATIONS (SHOCK AND VIBRATION SPECIFICATIONS)

The component shock and vibration requirements were determined from finite element model predictions, above ground test data, underground test data, and flight test data. The environments were grouped into three categories: 1) transportation shock and vibration; 2) flight shock and vibration; and 3) hostile shock. Shock and vibration test specifications were developed at four levels: system (full-body), subsystem (electronics package), components (radar, programmer, batteries, etc.), and individual circuits (chips, relays, etc.). Component level testing was the primary means of verifying the design adequacy to shock and vibration loads. This was due to the difficulty in achieving realistic component responses in some of the system level simulation tests.

Shock and vibration environments were enveloped from the three different categories. Only environments of similar time-history characteristics were included in each envelope. The final component test specifications consisted of:

1) one transportation shock test (drop table technique)
2) one transportation sine vibration test (alternative random vibration test)
3) one flight sine vibration test
4) two flight random vibration tests
5) one flight shock test (repeated four times)
6) two hostile shock tests

Transportation environments are not typically a problem for electronic components. Therefore, these tests included the most amount of conservatism and the least amount of realism, but they are very simple to perform. For flight and hostile environments, an attempt was made to realistically simulate the environments. The flight shock specifications were defined in terms of decayed sinusoids for shake table testing. The hostile shock specifications were defined for resonant plate tests due to frequency and g-levels that exceeded the shaker shock test capabilities.

An attempt was made to indirectly achieve both time history and shock spectrum input control even for the resonant plate test. This is an area where further development is definitely needed, because the simultaneous matching of time history and shock spectrum inputs is the best current method for specifying a meaningful shock test. It is a distinct move in the direction of defining and reproducing the input field environment for the component. Other techniques are currently under development for simulating the true characteristics of field environments, including probabilistic methods (16-18).

The re-entry vehicle component flight shock test specifications are shown in Figures 7a-b. Figures 8a-b show the flight sine and random vibration specifications, respectively. Figure 9 shows the hostile shock specification using the resonant plate test.

Because there is not a high degree of direct control over the time history reproduction in the resonant plate technique, there is conservatism built into the test. However, based upon a knowledge of the technique, and the field data, one can determine the appropriate test levels to specify. Note that in many cases, this implies that the test specification will not envelope the shock spectra data at every point in the spectrum. An example illustrates this point.

Figures 3a-b show the time history and shock spectrum for a re-entry vehicle component from a single impulse test. This is one of the field environments that is included in Figure 4a. Figures 10a-b show the results of a resonant plate test at the production agency, indicating the success they had in duplicating the desired test inputs. Note that the peak-g in the individual field event (Figure 3a) is less than 1500g; however, the peak-g required in the component test (Figure 10a) to meet the specification shown in Figure 4b was between 2500 g - 3000 g. This represents a significant amount of conservatism when comparing time history information, even though the shock spectrum comparison does not show that amount of conservatism.

A typical problem that occurs with this type of testing is that often there is a significant amount of overtesting due to fixture dynamic amplification. Also, the shock is a single input but the limitations of the testing and fixturing typically require that the test consist of three separate inputs in three mutually perpendicular axes. Sometimes, the fixturing lends itself to the situation where two axes of the requirements can be simultaneously achieved. Therefore, if possible, cross-axis coupling effects and fixture amplifications should be characterized and utilized to reduce the amount of conservatism. This was done for some of the components in the re-entry vehicle.

VIII. GENERAL COMMENTS REGARDING CURRENT CAPABILITIES IN COMPONENT SPECIFICATIONS

The current modeling and analysis support for component specifications requires the use of finite element models. The analysis can now make use of fully 3-D models for the vibration and shock response predictions. Ground test simulation of flight environments is very difficult to achieve. This is primarily due to boundary condition differences that exist between ground and field test conditions.

Currently, component specifications exist up to 4000 Hz in vibration and 10,000 Hz in shock. At these frequencies input averaging and fixture dynamic effects must be properly treated. Component level testing is still the primary means for qualifying weapon systems to shock and vibration loads. Shock specifications for oscillatory shock events can now be defined using resonant plate techniques. Although the shock test input is defined in terms of shock spectra, this allows an indirect control over the time history as well. This represents a distinct move in the direction of defining and reproducing the input field environment for the component.

Continued improvement in analysis and modeling techniques is needed to allow for the accurate prediction of full-body structural shock response up to 10,000 Hz. Improvements are also needed in ground testing to better simulate actual use conditions. Specification procedures for resonant plate tests need to be simplified for production agency applications.

Fixturing dynamic effects must be directly incorporated into component qualification testing to reach frequency ranges of 4000 Hz in vibration and 10,000 Hz in shock. Averaged input control should be used for vibration, and fixture gradient and cross-coupling effects should be utilized for shock. Also, improved analytical support is needed in the areas of measurement, instrumentation, and data analysis to ensure the validity of the measured field data.

Finally, the results of our experiences with the re-entry vehicle applications have yielded some general recommendations for component shock and vibration testing. All components that are required for a given system should utilize the same philosophy for determining their qualification tests, lot sample tests, and 100% testing. The component development testing should include testing to failure in sine vibration, random vibration and shock. Extensive fixture design and development testing should be performed before defining the test specifications. All evaluation testing should be performed during development, and no new testing requirements should be introduced during production testing. Different tests may be specified for production, but they should be selected based upon the same philosophy and the knowledge of the failure threshold of the component to that type of environment.

IX. CONCLUSIONS

Electronic components used in some system applications must be qualified to severe mechanical shock and vibration environments. Often production of these environments in the laboratory requires the development and use of special qualification testing techniques and procedures. The specification development process requires the interaction of modeling, analysis, test support, signal processing and data analysis. Component level testing is the primary means for qualifying weapon systems to shock and vibration loads. However, the system and subsystem environment definition and testing is a necessary intermediate step in the process. These activities require the application of technical expertise in a wide variety of areas.

The difference between environmental specifications and test specifications is an important one. In particular, the characterization of shock data requires both time-domain and frequency-domain descriptions of the data. The resonant plate shock testing technique, a new technique for simulating severe shock environments, is now available for simulating high g-level, and high frequency oscillatory pulses. This often provides a much better simulation to the actual field environment than current drop table techniques. The goal is not only that the components survive the test inputs, but that the test inputs truly represent the environments experienced in the field.

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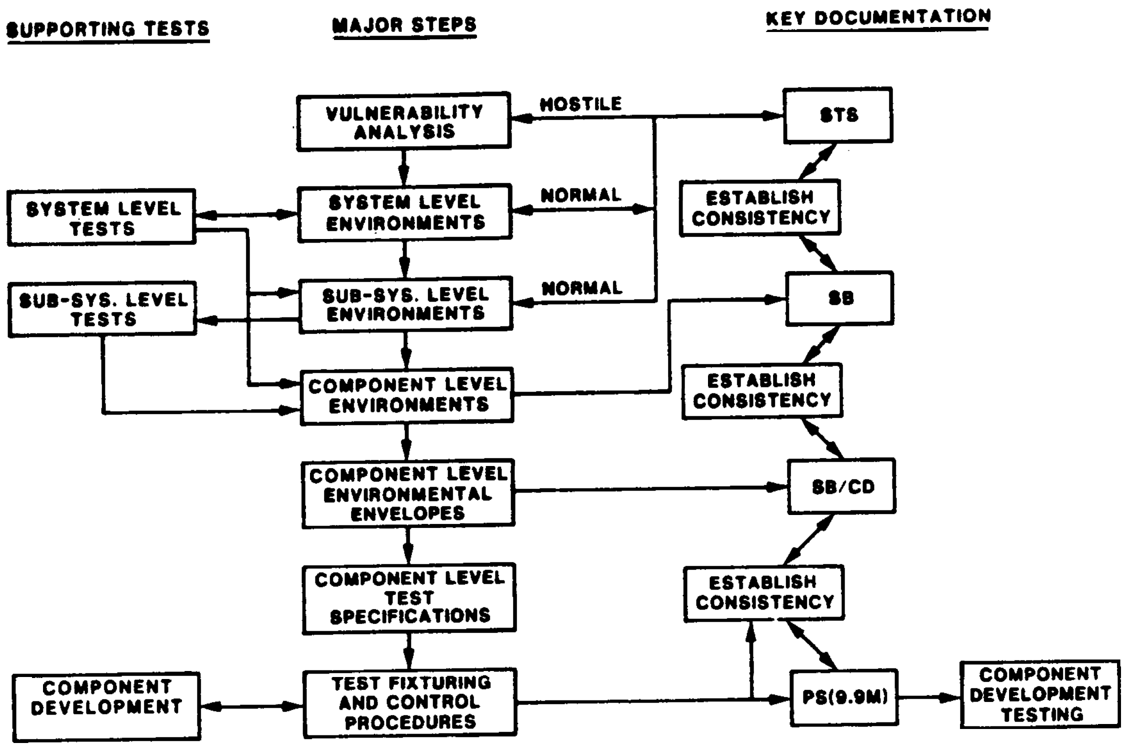

FIGURE 1. Component Specification Process

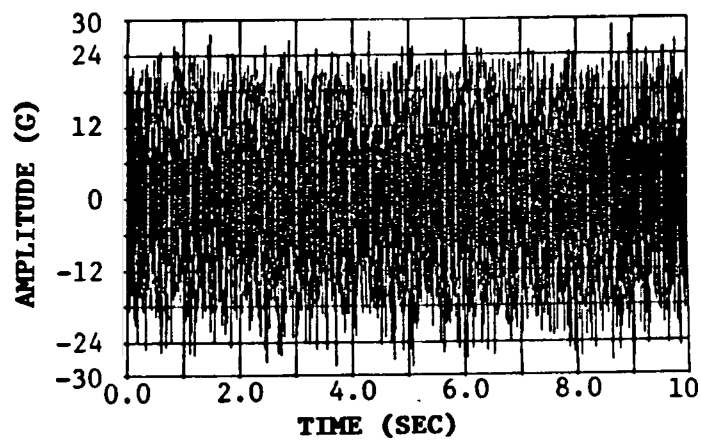

FIGURE 2a. Random Vibration - Time History

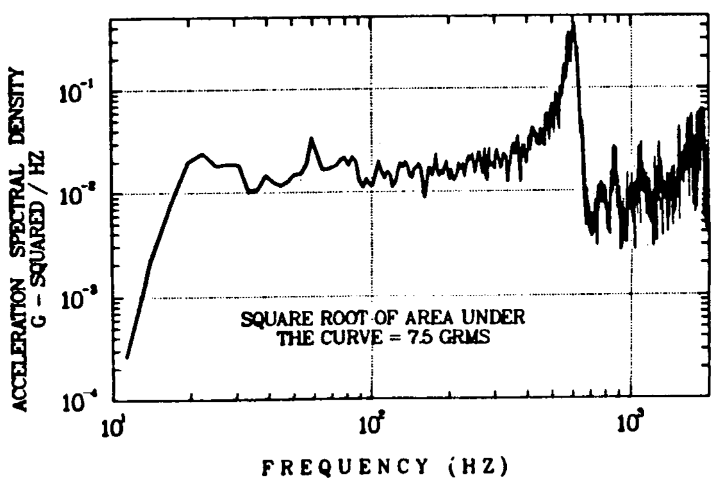

FIGURE 2b. Random Vibration - Power Spectral Density

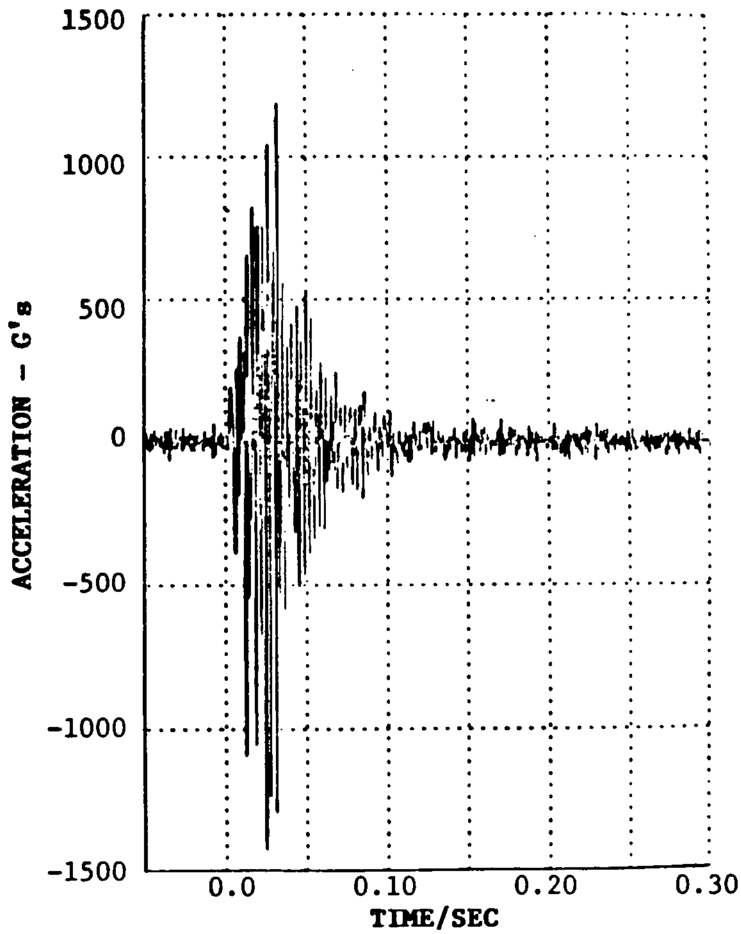

FIGURE 3a. Component Shock Event: Acceleration Time History

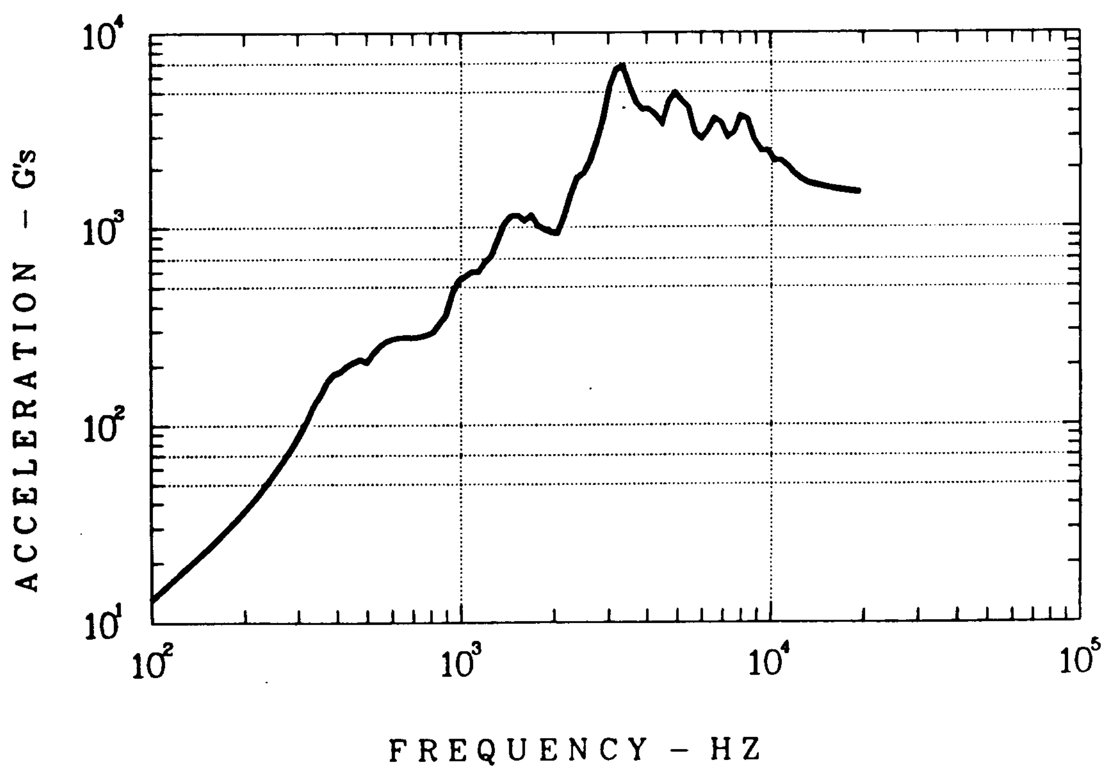

FIGURE 3b. Component Shock Event - Shock Spectrum

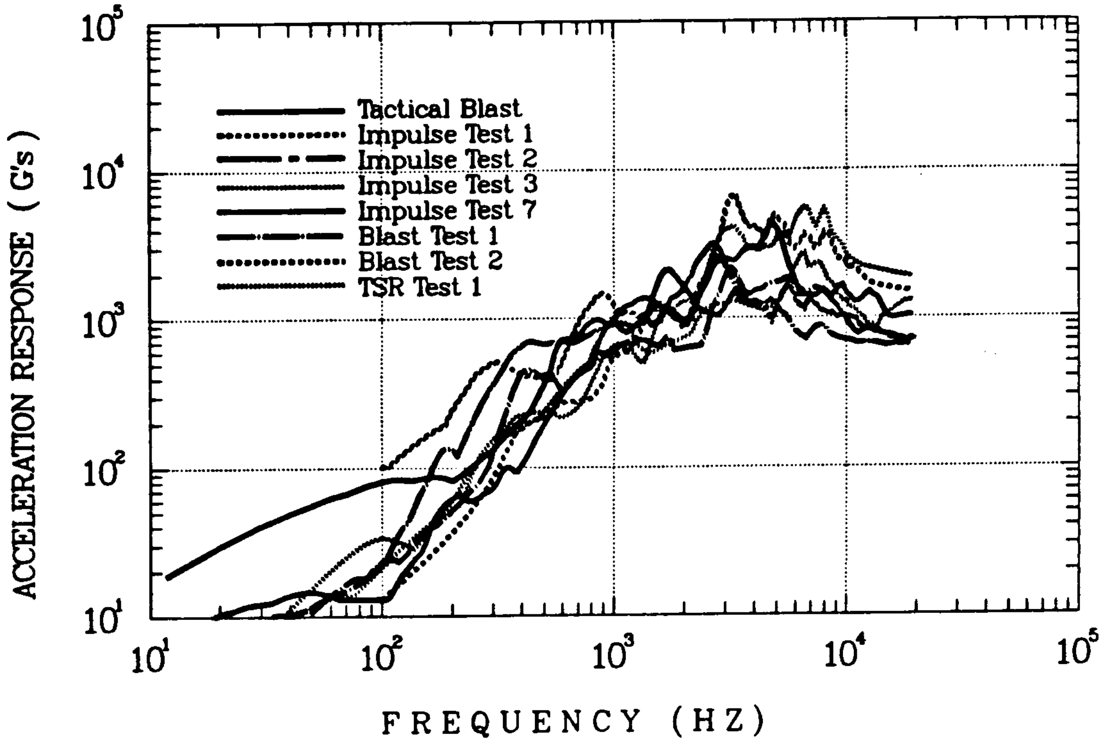

FIGURE 4a. Component Shock Spectrum - Environmental Specification

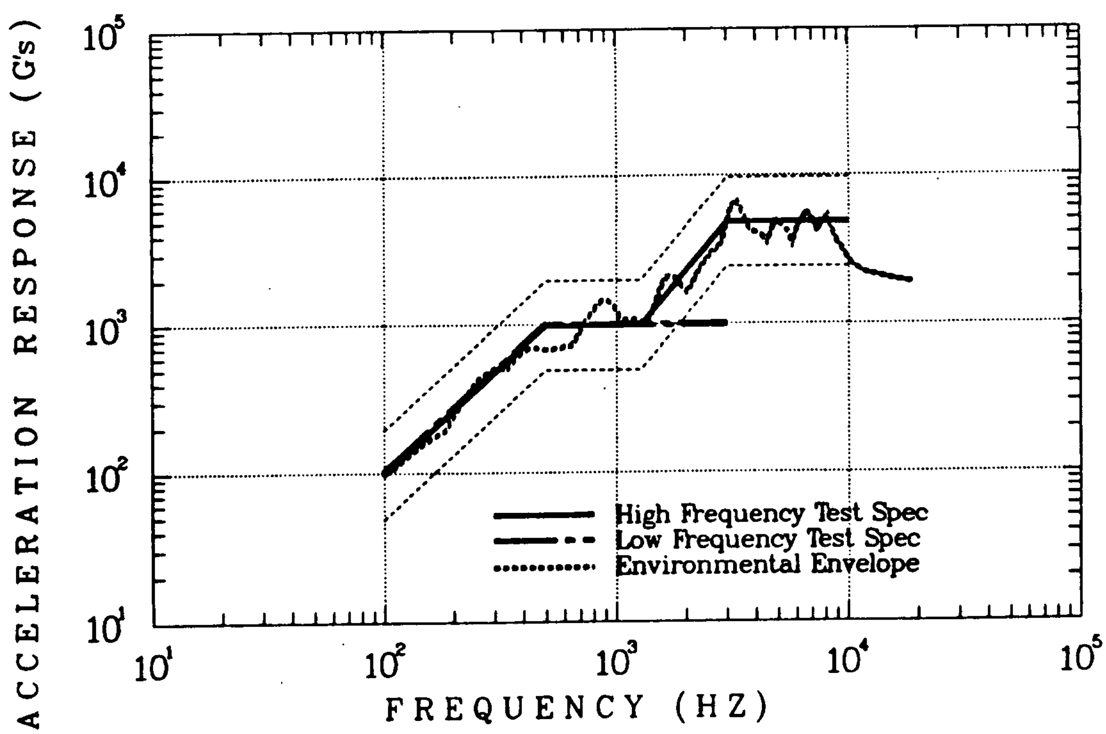

FIGURE 4b. Component Shock Spectrum - Test Specification

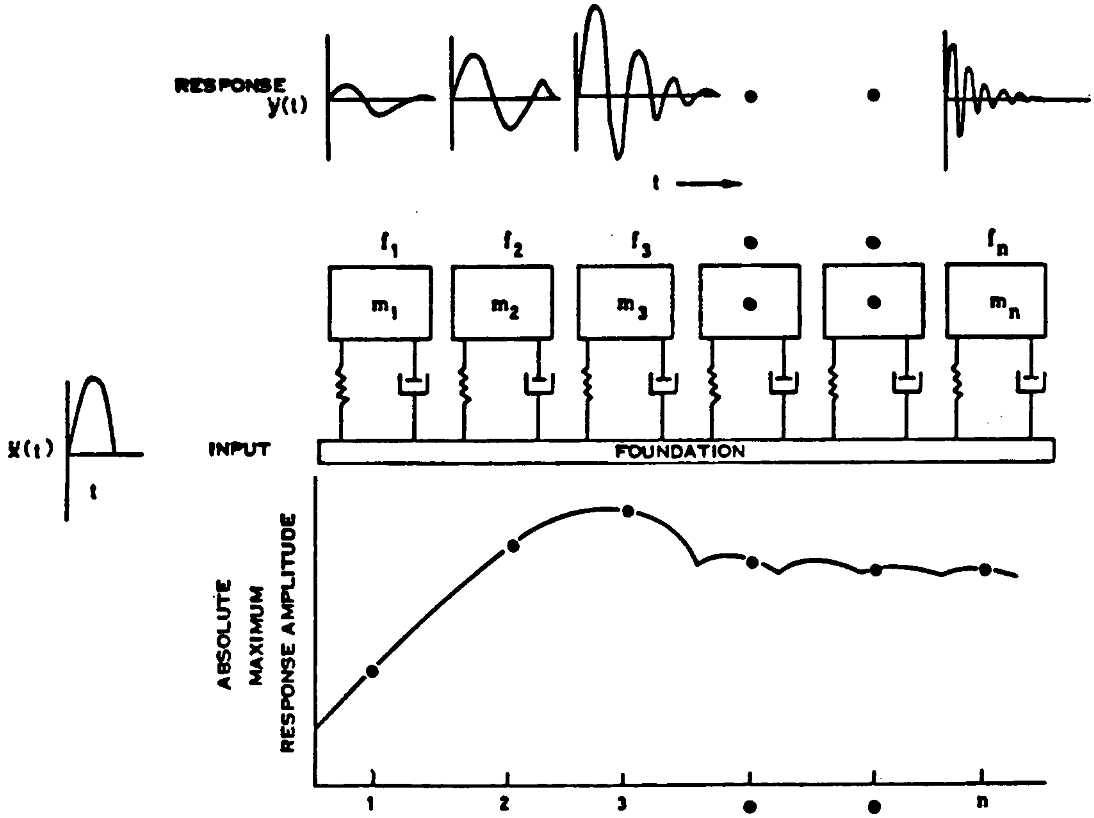

FIGURE 5. Shock Spectrum Description

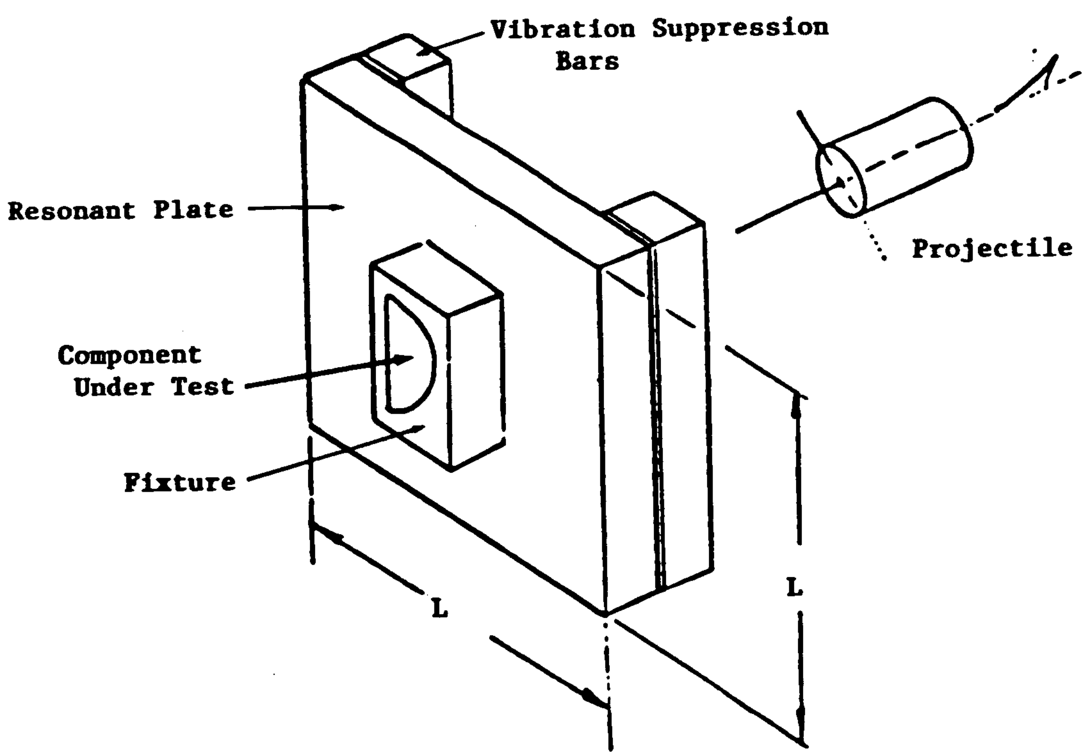

FIGURE 6. Resonant Plate Test

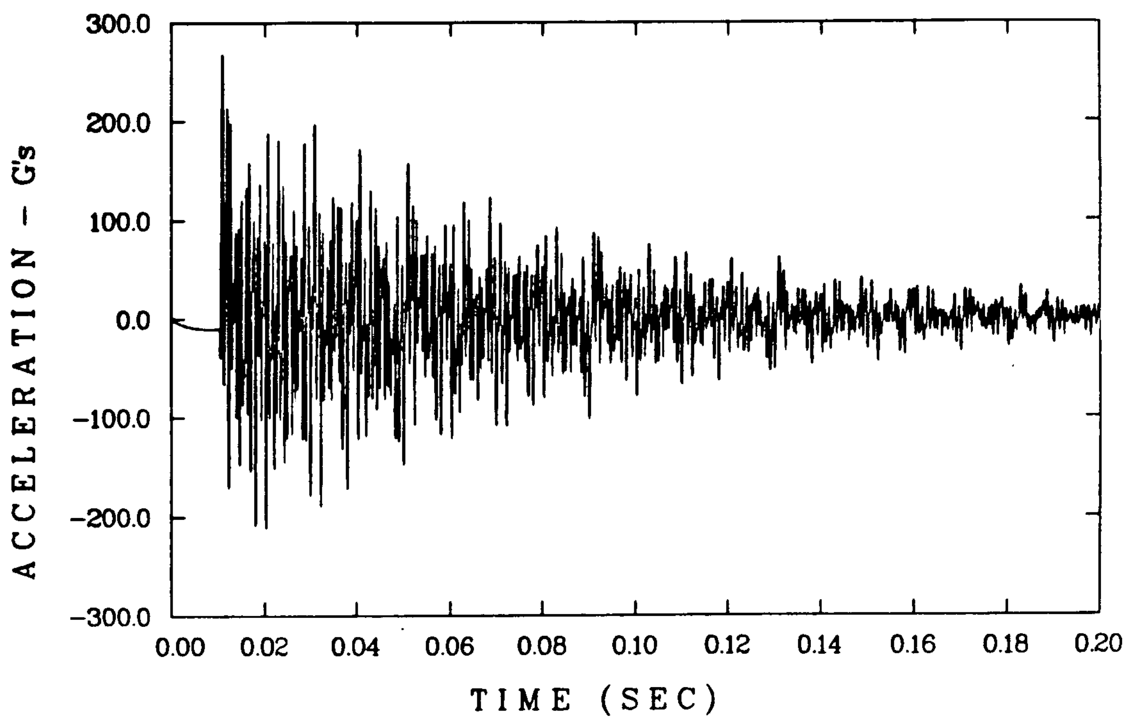

FIGURE 7a. Component Flight Shock Specification: Time History Decayed Sinusoid Shake Table Test

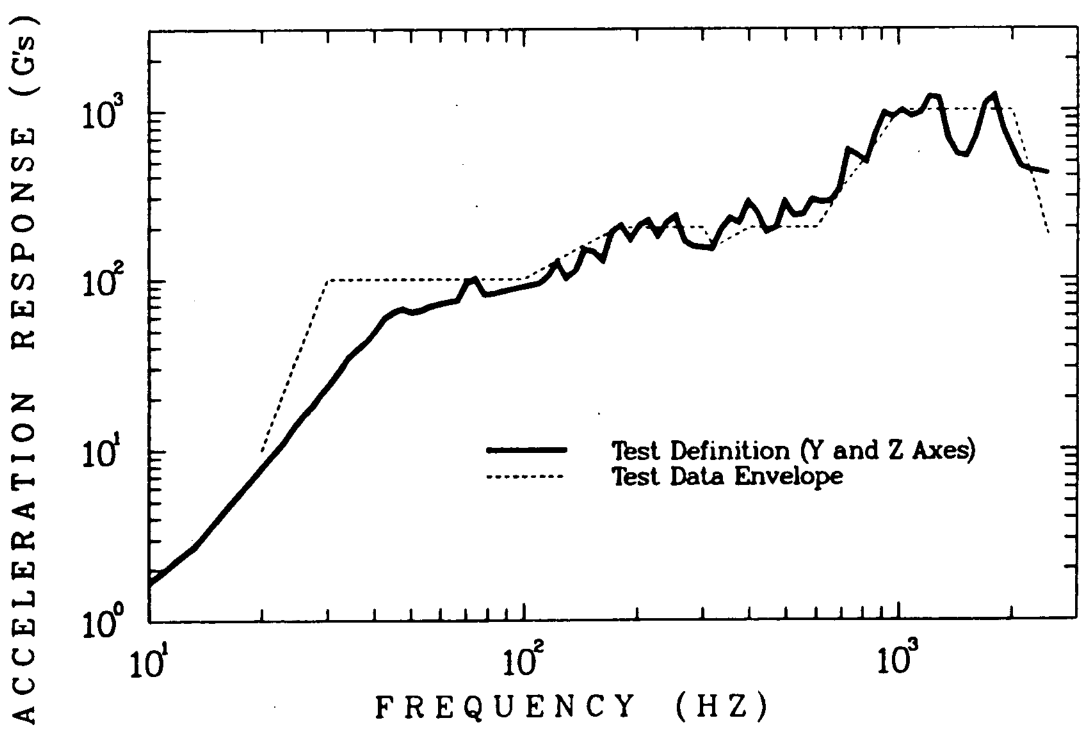

FIGURE 7b. Component Flight Shock Specification: Shock Spectrum Decayed Sinusoid Shake Table Test

QUALIFICATION TEST FOR THE AF&F MC3810 COMPONENTS TO LONG DURATION SINUSOIDAL VIBRATION

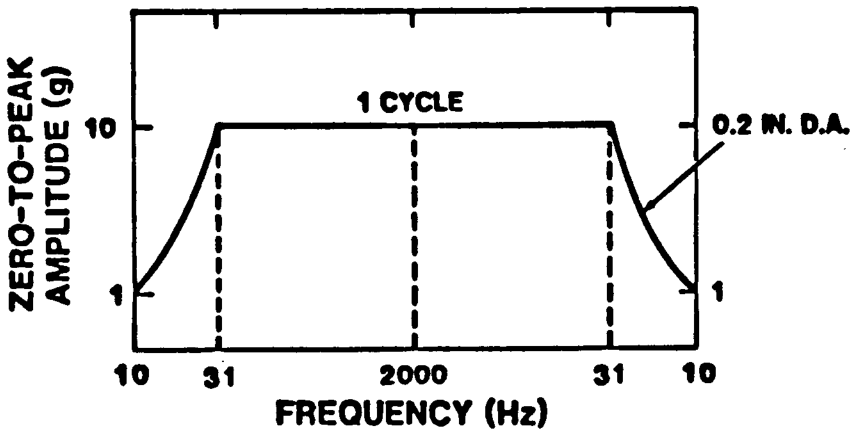

FIGURE 8a. Component Sine Vibration Specification

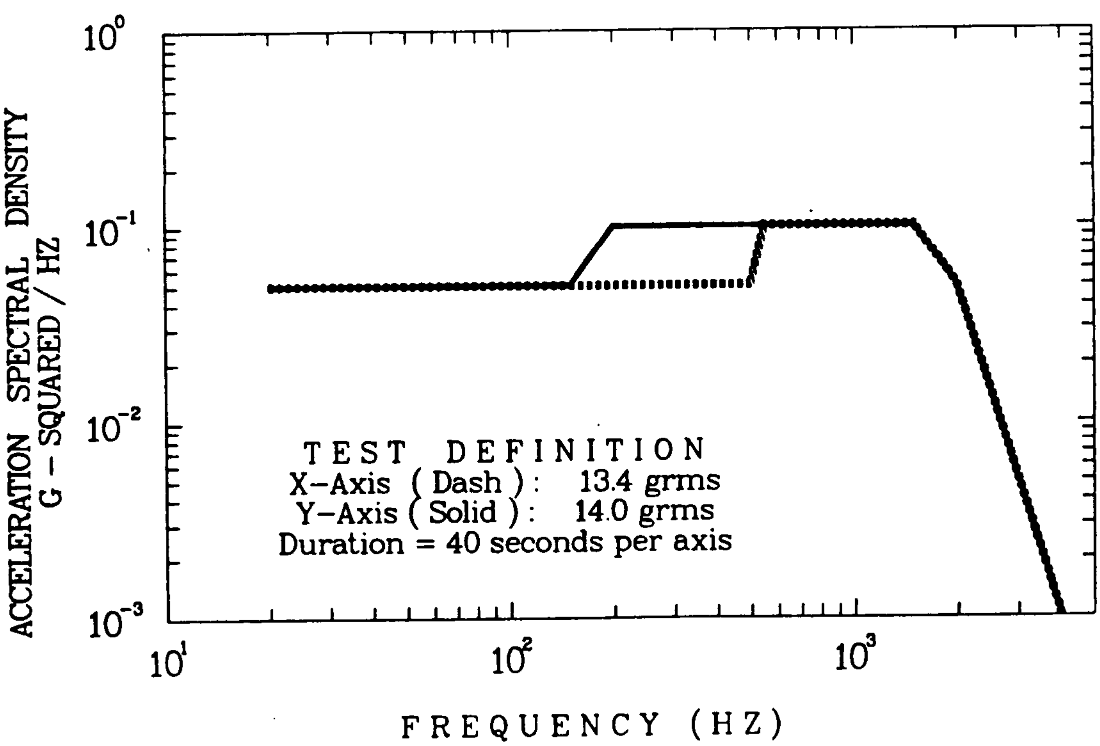

FIGURE 8b. Component Random Vibration Specification

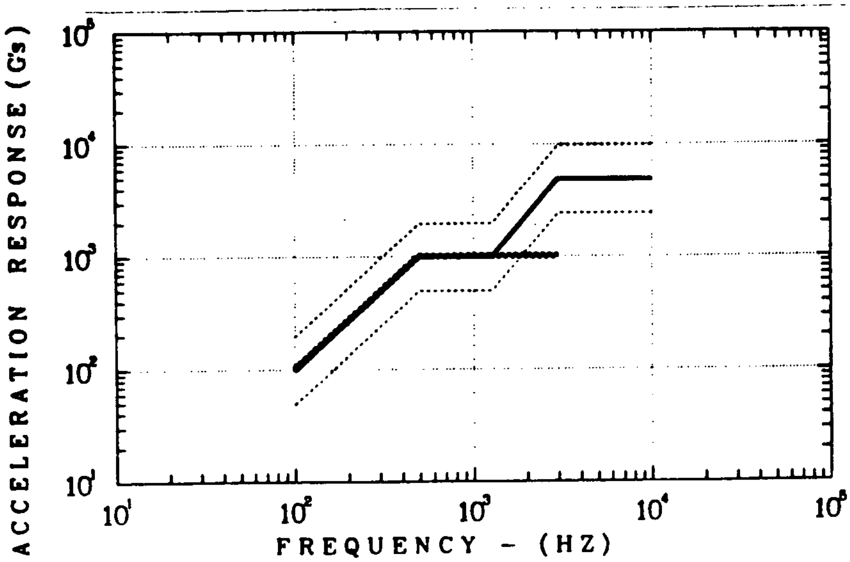

FIGURE 9. Component Hostile Shock Specification: Shock Spectrum Resonant Plate Test

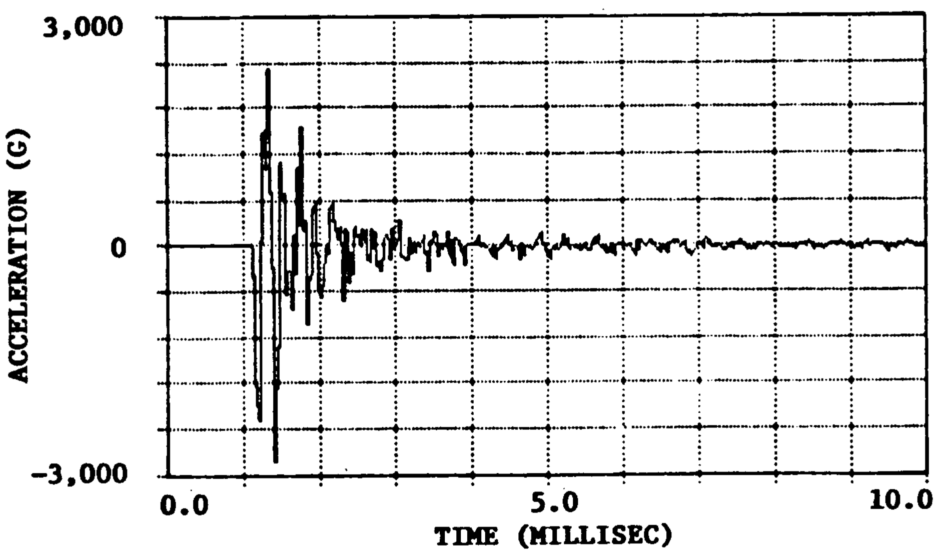

FIGURE 10a. Component Hostile Shock Implementation at Production Agency: Time History

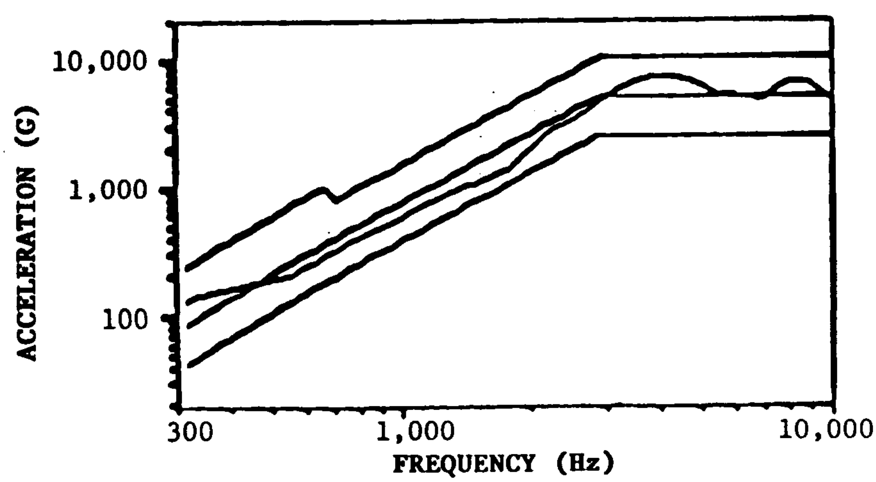

FIGURE 10b. Component Hostile Shock Implementation at Production Agency: Shock Spectrum