CHAPTER 20

TEST CRITERIA AND SPECIFICATIONS

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INTRODUCTION

This chapter covers the development of shock and vibration test criteria for mechanical, electrical, electronic, or hydraulically powered equipment, for example, an alternator for an automobile or an electronic instrument for an airplane. The emphasis throughout is on the selection of test criteria rather than the formulation of design criteria, but specified shock and vibration test levels and durations are commonly used as design criteria as well. Following a brief overview of environmental specifications, this chapter presents (1) a summary of the descriptions of shock and vibration environments used to establish test criteria, (2) a discussion of the different types of tests used to achieve various objectives, (3) procedures to select shock and vibration test levels, (4) procedures to select vibration test durations, and (5) general testing considerations.

ENVIRONMENTAL SPECIFICATIONS

An *environmental specification* is a written document that details the environmental conditions under which an item of equipment to be purchased must operate during its service life. Several contracting agencies of the U.S. government and various professional societies issue general environmental specifications for particular classes of equipment (see Chap. 19), but deviations from the specified environmental conditions in such documents are permitted when more appropriate conditions can be established by direct measurements or predictions of the environments of concern. An *environmental test specification* is a written document that details the specific criteria for an environmental test, as well as other matters such as the preparation of the test item, identification of all test equipment and instrumentation, description of any test fixtures, instructions for mounting sensors, step-by-step procedures for operating the test item (if operation is required), procedures for taking data on the test item function and the applied environment, and performance acceptability criteria. The test criteria (the magnitude and duration of the test excitation) in environmental test specifications often serve as design criteria as well (see Chap. 41).

GENERAL TYPES OF ENVIRONMENTS

The environments that must be considered in equipment design and testing are listed in Table 20.1. Those printed in boldface, namely, shock and vibration, are the ones of special concern in this handbook. Shock and vibration environments may result from the equipment operation (for example, the vibration caused by shaft unbalance in equipment with a rotating element), but it is the external shock and vibration motions transmitted into the equipment through its mounting points to the structure of the system incorporating the equipment that are of primary interest here. The acoustical, blast, fluid flow, and wind environments noted in Table 20.1 are often the original source of the shock and vibration motions of the system structure that transmit into the equipment, but the original source may also be a direct motion input to the system, for example, earthquake inputs to a building or road roughness inputs to an automobile. Such environments have complicated transmission patterns that are modified or intensified by mechanical resonances of the system structure and, therefore, are appropriately described by frequency-dependent functions, i.e., spectra.

TABLE 20.1 Various Types of Environments to Which Equipment May Be Exposed

Acceleration (sustained)	Fungus	Salt spray
Acoustical noise	Humidity	Temperature (sustained)
Blast	**Mechanical shock**	Temperature cycling
Dust and sand	Pressure (sustained)	**Vibration**
Fluid flow	Rain, hail, and snow	Wind

In practice, for economy of effort, equipment is often designed and tested for exposure to each of the environments listed in Table 20.1 as if they occur separately. However, some of the environments in Table 20.1 may occur simultaneously and have an additive effect; for example, a shock may occur during a period of high static acceleration where the stress in the equipment due to the combination of the two environments is greater than the stress due to either applied separately. Worse yet, two environments may have a synergistic effect; for example, equipment may be subject to high vibration during a period when the temperature exposure is also high, and high temperatures cause a degradation of the equipment strength, making it more vulnerable to vibration-induced failures. These matters must be carefully evaluated during the definition of a test program to determine if simultaneous testing for two or more environments is required.

SHOCK AND VIBRATION ENVIRONMENTS

From a testing viewpoint, it is important to carefully distinguish between a shock environment and a vibration environment. In general, equipment is said to be exposed to *shock* if it is subject to a relatively short-duration (transient) mechanical excitation; equipment is said to be exposed to *vibration* if it is subject to a longer-duration mechanical excitation. If the basic properties of the vibration are time-invariant, it is called *stationary* (or steady-state for periodic vibrations). However, vibration environments are often *nonstationary,* i.e., one or more of their basic properties vary with time. If the properties change slowly relative to the lowest frequency of the vibration, then the vibration can be analyzed to arrive at criteria for a stationary vibration test, as detailed later. Otherwise, the environment must be viewed as a shock. Practical distinctions between shock and vibration environments cannot be made on an absolute basis, independent of the equipment exposed to the environment. To be more specific, any mechanical device that is more or less linear can be characterized by one or more resonance frequencies and damping coefficients (see Chap. 2) or by a corresponding set of decaying transient responses after a momentary excitation. In more analytical terms, the response characteristics of a mechanical device are given by the *unit impulse response function* defined in Chap. 21. From a testing viewpoint, an excitation whose duration is comparable to, or less than, the response (or decay) time of the equipment is considered a shock, while an excitation whose duration is long compared to the response time of the equipment is considered a vibration.

DESCRIPTIONS OF SHOCK AND VIBRATION ENVIRONMENTS

The response of equipment to shock and vibration at its mounting points is dependent on frequency. Hence, shock and vibration environments are usually described by some type of spectrum; a *spectrum* is a description of the magnitude of the frequency components that constitute the shock or vibration. The most common spectral descriptions of both deterministic and random shock and vibration environments are summarized in Table 20.2 (see Chaps. 22 and 23 for details). It is common to present data for test specification purposes in terms of acceleration, primarily because it is convenient to measure acceleration with accelerometers described in Chap. 12. However, for shock data presented in the form of a shock response spectrum, a response in terms of velocity or pseudo-velocity (see Chap. 41) is often preferred to acceleration. This is because the shock response spectrum represents the peak response of a single degree-of-freedom system, and modal (relative) velocity for such a response has a direct linear relationship to stress[2,3] [see Eq. (26.1)]. Nevertheless, the use of an acceleration parameter for shock response spectra is not a problem in specifying test criteria as long as the criteria simulate the spectrum of the environment, and acceleration is used for both the environmental description and the test criteria.

TABLE 20.2 Common Spectral Descriptions of Shock and Vibration Environments

Environment	Characteristic	Spectral description
Shock	Deterministic	Fourier (integral) spectrum (see Chap. 23) Shock response spectrum (see Chaps. 8 and 23)
	Random	Energy spectral density (see Chap. 11 and Ref. 1) Shock response spectrum (see Chaps. 8 and 23)
Vibration	Deterministic	Line spectrum (see Chap. 22)
	Random	Power spectral density (see Chaps. 11 and 22)

The vibration environment for an item of equipment usually varies in magnitude and spectral content during its service life. Similarly, a shock environment may involve repetitive shocks with different magnitudes and spectral content. For reliability tests discussed later in this chapter, it may be necessary to measure or predict the spectra of the shock and/or vibration environment for all conditions (or a representative sample thereof) throughout the service life and to formulate test criteria that require a series of tests with several different magnitudes and spectral content. For most testing applications, however, a test involving a single spectrum is desired for convenience. To assure that the test produces a conservative result, a maximax spectrum is used; a *maximax spectrum* is the envelope of the spectra for all conditions throughout the service environment. Thus, the maximax spectrum may not equal any of the individual spectra measured or predicted during the service environment, since the maximum value at two different frequencies may occur at different times.

TYPES OF SHOCK AND VIBRATION TESTS

An *environmental test* is any test of a device under specified environmental conditions (or sometimes under the environment generated by a specified testing machine) to determine whether the environment produces any deterioration of performance or any damage or malfunction of the device; an environmental test may also be distinguished by the objectives of the test. In assessing the effects of shock and vibration on equipment, the types of tests most commonly performed fall into the following categories:

1. Development
2. Qualification
3. Acceptance
4. Screening
5. Statistical reliability
6. Reliability growth

DEVELOPMENT TESTS

A *development test* (sometimes called an *analytical test*) is a test performed early in a program to facilitate the design of a device or piece of equipment to withstand its anticipated service environments. It may involve determining the resonance frequency of a constituent component mounted inside the equipment by applying a sinusoidal excitation with a slowing-varying frequency (often called a *swept sine wave* test). Sinusoidal vibration is widely used as the excitation for development tests because of its simplicity and well-defined deterministic properties. In contrast, it may involve a more elaborate test to determine the normal modes and damping ratio of the equipment structure as described in Chap. 21. A stationary random vibration or a controlled shock excitation with appropriate data reduction software can greatly reduce the time required to perform a more extensive modal analysis of the equipment. In either type of test, the characteristics and magnitude of the excitation used for the test are not related to the actual shock and/or vibration environment to which the equipment is exposed during its service use.

QUALIFICATION TESTS

A *qualification test* is a test intended to verify that an equipment design is satisfactory for its intended purpose in the anticipated service environments. Such a test is commonly a contractual requirement, and hence, a specific test specification is usually involved. Preliminary qualification tests are sometimes performed on prototype hardware to identify and correct design problems before the formal qualification test is performed. Also, qualification test requirements might be based upon a general environmental specification (see Chap. 19). In some cases, the specification may require a test on a specific type of testing machine that produces a desired qualification environment (see Chap. 26). However, contracts usually allow deviations from the specified test levels and/or test durations in general environmental specifications, if it can be established that different test conditions would be more suitable for the given equipment. In any case, the basic purpose of a qualification test requires that the test conditions conservatively simulate the basic characteristics of the anticipated service environments.

Some years ago, when test facilities were more limited, it was argued that shock and vibration environments for equipment could be simulated for qualification test purposes in terms of the damaging potential of the environment, without the need for an accurate simulation of the detailed characteristics of the environment.[4] For example, it was assumed that random vibration could be simulated with sinusoidal vibration designed to produce the same damage. The validity of such "equivalent damage concepts" requires the assumption of a specific damage model to arrive at an appropriate test level and duration. Since the assumed damage model might be incorrect for the equipment of interest, there is a substantial increase in the risk that the resulting test criteria will severely under- or overtest the equipment. With the increasing size and flexibility of modern test facilities, the use of equivalent damage concepts to arrive at test criteria is rarely required and should be avoided, although equivalent damage concepts are still useful in arriving at criteria for "accelerated tests," as discussed later in this chapter. When ever feasible, *qualification tests should be performed using an excitation that has the same basic characteristics as the environment of concern; for example, random vibration environments should be simulated with random vibration excitations, shock environments should be simulated with shock excitations of similar duration, etc.*

ACCEPTANCE TESTS

An *acceptance test* (sometimes called a *production test* or a *quality control test*) is a test applied to production items to help ensure that a satisfactory quality of workmanship and materials is maintained. For equipment whose failure in service might result in a major financial loss or personal injury, all production items are subjected to an acceptance test. Otherwise, a statistical sample of production items is selected, and each item is tested in accordance with an acceptance sampling plan that assures an acceptable average outgoing quality.[5] In either case, there are two basic approaches to acceptance testing for shock and vibration environments. The first approach is to design a test that will quickly reveal common workmanship errors and/or material defects as determined from prior experience and studies of failure data for the equipment, independent of the characteristics of the service environment. For example, suppose a specific type of electrical equipment has a history of malfunctions induced by scrap-wire or poorly soldered wire junctions. Then, the application of sinusoidal vibration at the resonance frequencies of wire bundles will quickly reveal such problems and, hence, constitute a good test excitation even though there may be no sinusoidal vibrations in the service environment. The second and more common approach is to apply an excitation that simulates the shock and/or vibration environments anticipated in service, similar to the qualification test but usually at a less conservative (lower) level.

SCREENING TESTS

A *screening test* is a test designed to quickly induce failures due to latent defects that would otherwise occur later during service use so that they can be corrected before delivery of the equipment, i.e., to detect workmanship errors and/or material defects that will not cause an immediate failure, but will cause a failure before the equipment has reached its design service life. Screening tests are similar to acceptance tests, but usually are more severe in level and/or longer in duration. If performed at all, screening tests are usually applied to all production items. Vibration screening tests are commonly performed with the simultaneous application of temperature cycling, a process referred to as environmental stress screening (ESS). The vibration environment is sometimes applied using relatively inexpensive, mechanically or pneumatically driven vibration testing machines (often referred to as impact or repetitive shock machines) that allow little or no control over the spectrum of the excitation (see Chap. 25). Hence, except perhaps for the overall level, the screening test environment generally does not represent an accurate simulation of the service environment for the equipment.

STATISTICAL RELIABILITY TESTS

A *statistical reliability test* is a test performed on a large sample of production items for a long duration to establish or verify an assigned reliability objective for the equipment operating in its anticipated service environment, where the reliability objective is usually stated in terms of a mean-time-to-failure (MTTF), or if all failures are assumed to be statistically independent, a mean-time-between-failures (MTBF) or failure rate (the reciprocal of MTBF). To provide an accurate indication of reliability, such tests must simulate the equipment shock and vibration environments with great accuracy. In some cases, rather than applying stationary vibration at the measured or predicted maximax levels of the environment, even the nonstationary characteristics of the vibration are reproduced, often in combination with shocks and other environments anticipated during the service life. The determination of reliability is accomplished by evaluating the times to individual failures, if any, by conventional statistical techniques.[6]

RELIABILITY GROWTH TESTS

A *reliability growth test* is a test performed on one or a few prototype items at extreme test levels to quickly cause failures and thus identify weaknesses in the equipment design. In many cases, the test level is increased in a stepwise manner to clearly identify the magnitude of the load needed to cause a specific type of failure. Design changes are then made and the failure rate of the equipment is monitored by either statistical reliability tests in the laboratory or evaluations of failure data from service experience to verify that the design changes produced an improvement in reliability.

Unlike statistical reliability tests, reliability growth tests do not simulate the magnitudes of the service environments, although some effort is often made to simulate the general characteristics of the environments; for example, random vibration would be used to test equipment exposed to a random vibration service environment.

SELECTION OF SHOCK AND VIBRATION TEST LEVELS

The *test level* for a shock or vibration test is the spectrum of the excitation applied to the equipment at its mounting points by the test machine. For tests that require a simulation of the actual service shock and vibration environments (qualification, reliability, and some acceptance tests), the selection of test levels involves four steps, as follows:

1. Measurement or prediction of spectra for shock and vibration environments
2. Grouping of measured or predicted spectra into appropriate zones
3. Determination of zone limits
4. Selection of specified test levels

MEASUREMENT OR PREDICTION OF SPECTRA

Where equipment is to be installed in an existing system (for example, a new alternator for an existing automobile), the shock and/or vibration response of the system structure at the mounting points of the equipment can be determined by direct measurements (see Chap. 15). However, where equipment is to be installed in a system that has not yet been built and/or operated, the shock and/or vibration environment at the equipment mounting points must be predicted. Procedures for the prediction of shock and vibration environments vary widely depending upon the characteristics of environment and the system producing it. In general, however, prediction procedures can be divided into the following broad categories:

Analytical Modeling Procedures. At least crude predictions for the shock and vibration response of a structural system at the mounting points of equipment can be achieved using the various analytical formulations detailed in other chapters in this handbook (for example, see Chaps. 1 through 3). The accuracy of the resulting shock and vibration predictions depends heavily upon the complexity of the system structure being modeled and the exact analytical modeling procedure used.

Finite Element Method (FEM) Procedures. A popular modeling procedure for the prediction of shock and vibration environments is the finite element method (FEM) detailed in Chap. 28, Part II. Properly characterized shock and vibration excitations can be applied to an FEM model to predict the structural response at any point of interest. The FEM model can also be used to compute the frequency response functions between excitation and response points needed to make predictions by the frequency response procedures discussed later. Depending on the complexity of the structure being modeled, FEM procedures can generally produce reasonably accurate shock and vibration predictions up to a frequency equivalent to about the 50th normal mode of the structure.

Statistical Energy Analysis (SEA) Procedures. At frequencies above the range where finite element method procedures are accurate, statistical energy analysis (SEA) procedures described in Chap. 11 are commonly used to predict vibration environments. Specifically, as frequency increases, the response of the system structure can be predicted in terms of the space-averaged response for each of a set of individual structural elements that are coupled to collectively describe the system, where each element has near-homogeneous properties and light damping; an example is a constant thickness panel. Such prediction procedures can be applied to a wide range of structural systems if the assumptions detailed in Chap. 11 are satisfied.

Frequency Response Procedures. For those structural systems where the shock and/or vibration environment is due to motion excitations at one or more points (for example, the response of an automobile to road roughness inputs at the four wheels), responses at various points on the system structure can be predicted using the input/output relationships detailed in Chap. 21, which involve the frequency response function defined in Eq. (21.10). Such frequency response functions for the system between the excitation points on the system and the mounting points of the equipment can be estimated either by using an FEM model described in Chap. 28, Part II, or by experimental measurements described in Chap. 21. These estimated frequency response functions can then be used to predict the response at the equipment mounting points for any arbitrary excitation spectra.

Extrapolation Procedures. The spectra of the responses measured on one system during its operation can often be used to predict the spectra in a newer model of the system, assuming the old and new systems have a similar purpose and are of broadly similar design, for example, a new airplane that flies faster but otherwise is similar in structural design to an earlier model of the airplane. In such cases, the shock and/or vibration responses of the new system at the structural locations of equipment can be predicted, at least coarsely, by scaling the measurements made on the previous system based upon the differences in at least two parameters, namely, (1) the magnitude of the original excitation to the system structure and (2) the weight of the system structure at the points where the equipment is mounted. Specifically, as a first order of approximation, the shock and/or vibration magnitude on the new system can be assumed to vary directly with the magnitude of the excitation and inversely with the weight of the system structure. Such extrapolation techniques have been widely used to predict spectra for the vibration response of new aerospace vehicles[3] and can often be applied to other types of systems as well.

GROUPING OF MEASURED OR PREDICTED SPECTRA INTO ZONES

The shock and vibration response of system structures that support equipment are typically nonhomogeneous in space, sometimes to the extent that the spectra of the responses vary substantially from one mounting point to another for a single item of equipment. At relatively low frequencies, corresponding to frequencies below about the fiftieth normal mode of the system structure (see Chap. 21), finite element method (FEM) models for the system structure and the mounted equipment can be used to predict the motions at the specific equipment attachment points. It is more common, however, to define shock and vibration environments by making measurements or predictions at selected points on the system structure that do not correspond to the exact mounting points for equipment, or if they do, the equipment is not present during the measurements or accurately modeled for the predictions. Hence, it is necessary to separate the measured or predicted responses at various points on the system structure into groups, where the responses in each group have broadly similar spectra that can be represented for test purposes by a single spectrum. A *zone* is defined as a region on the system structure that includes those points where the measured or predicted shock and/or vibration responses have broadly similar spectra. It is clear that a zone should correspond to a region of interest in the formulation of shock and vibration test criteria for equipment, i.e., a single zone should include all the attachment points for at least one item of equipment, and preferably, for several items of equipment. However, a zone need not be a single contiguous structural region. For example, all frames of a given size in an airplane, no matter where they are located, might constitute a single zone if the responses of those frames are similar.

The determination of zones is usually based upon engineering judgment and experience. For example, given a system with frame-panel construction, engineering judgment dictates that frames and panels should represent different zones, since the responses of light panels will generally be greater than the much heavier frames. Also, the responses perpendicular to the surface of the panels are generally greater than the responses in the plane of the panels, so the responses along these two axes might be divided into separate zones. A visual inspection of the spectra for the measured or predicted responses also can be used to group locations with spectra of similar magnitudes to arrive at appropriate zones. In any case, it is desirable to minimize the number of zones used to describe the shock and vibration responses over those areas of the system structure where equipment will be mounted so as to minimize the number of individual spectra required to test all the equipment for that system.

DETERMINATION OF ZONE LIMITS

A *zone limit* (also called the *maximum expected environment*) is a single spectrum that will conservatively bound the measured or predicted spectra at most or all points within the zone, without severely exceeding the spectrum at any one point. A zone limit may be determined using any one of several procedures.[3,7] The most common procedure is to envelop the measured or predicted spectra in the zone, but a more rigorous approach is to compute a tolerance limit for the spectra. Specifically, given n measurements of a random variable x, an upper *tolerance limit* is defined as that value of x (denoted by L_x) that will exceed at least β fraction of all values of x with a *confidence coefficient* of γ. The fraction β represents the minimum probability that a randomly selected value of x will be less than L_x; the confidence coefficient γ can be interpreted as the probability that the L_x computed for a future set of data will indeed exceed at least β fraction of all values of x. Tolerance limits are commonly expressed in terms of the ratio $(100\beta)/(100\gamma)$. For example, a tolerance limit determined for $\beta = 0.95$ and $\gamma = 0.50$ is called the 95/50 normal tolerance limit. In the context of shock and/or vibration measurements or predictions, x represents the spectral value at a specific frequency (see Table 20.2) for the response of the system structure at a randomly selected point within a given zone, where x differs from point-to-point within the zone due to the spatial variability of the response. However, x may also differ due to other factors, such as variations in the response from one system to another of the same design or from one environmental exposure to another of the same system. In selecting a sample of measured or predicted spectra to compute a tolerance limit, beyond the spectra at different locations within a zone, it is wise to include spectra from different systems of the same design and different environmental exposures of the same system, if feasible, so that all sources of variability are represented in the measured or predicted spectra.

Tolerance limits are most easily computed when the random variable is *normally distributed* (see Chap. 11). The point-to-point (spatial) variation of the shock and vibration responses of system structures is generally not normally distributed, but there is empirical evidence that the logarithm of the responses does have an approximately normal distribution. Hence, by simply making the logarithmic transformation

$$y = \log_{10} x \tag{20.1}$$

where x is the spectral value at a specific frequency of the response within a zone, the transformed variable y can be assumed to have a normal distribution. For n sample values of y, a normal tolerance limit is given by[5]

$$L_y(n,\beta,\gamma) = \bar{y} + k s_y \tag{20.2}$$

where $\bar{y}$ is the sample average and s_y is the sample standard deviation of the n transformed spectral values computed as follows:

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \qquad s_y = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{20.3}$$

The term k in Eq. (20.2) is called the *normal tolerance factor* and is a tabulated value; a short tabulation of k for selected values of n, β, and γ, is presented in Table 20.3. The normal tolerance limit for the transformed variable y is converted to the original engineering units of x by

$$L_x(n,\beta,\gamma) = 10^{L_y(n,\beta,\gamma)} \tag{20.4}$$

To simplify test criteria, normal tolerance limits are often smoothed using a series of straight lines, usually no more than seven with slopes of 0, ±3, or ±6 dB.

TABLE 20.3 Normal Tolerance Factors for Upper Tolerance Limit

	$\gamma = 0.50$			$\gamma = 0.75$			$\gamma = 0.90$		
n	$\beta = 0.90$	$\beta = 0.95$	$\beta = 0.99$	$\beta = 0.90$	$\beta = 0.95$	$\beta = 0.99$	$\beta = 0.90$	$\beta = 0.95$	$\beta = 0.99$
3	1.50	1.94	2.76	2.50	3.15	4.40	4.26	5.31	7.34
4	1.42	1.83	2.60	2.13	2.68	3.73	3.19	3.96	5.44
5	1.38	1.78	2.53	1.96	2.46	3.42	2.74	3.40	4.67
7	1.35	1.73	2.46	1.79	2.25	3.13	2.33	2.89	3.97
10	1.33	1.71	2.42	1.67	2.10	2.93	2.06	2.57	3.53
15	1.31	1.68	2.39	1.58	1.99	2.78	1.87	2.33	3.21
20	1.30	1.67	2.37	1.53	1.93	2.70	1.76	2.21	3.05
30	1.29	1.66	2.35	1.48	1.87	2.61	1.66	2.08	2.88
50	1.29	1.65	2.34	1.43	1.81	2.54	1.56	1.96	2.74
∞	1.28	1.64	2.33	1.28	1.64	2.33	1.28	1.64	2.33

As an illustration, Fig. 20.1 shows the range of the maximax power spectra for $n = 12$ vibration measurements made at different locations in a selected zone of the structure of a large space vehicle during lift-off. Also shown in this figure are the unsmoothed and smoothed normal tolerance limit versus frequency computed with $\beta = 0.95$ and $\gamma = 0.50$ (the 95/50 limit). Note that the normal tolerance limit at most frequencies is higher than the largest of the 12 spectral values from which the limit is computed. However, a normal tolerance limit could be either higher or lower than the largest spectral values from which the limit is computed, depending on the values of n, β, and γ.

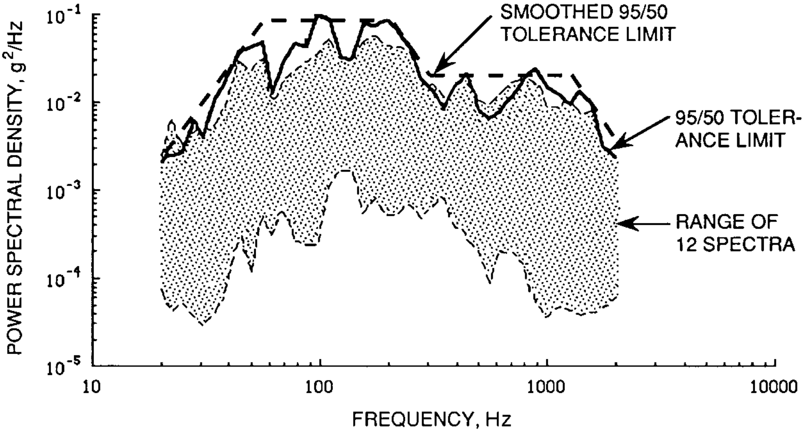

FIGURE 20.1 95/50 normal tolerance limit for spectra of 12 vibration measurements.

SELECTION OF FINAL TEST LEVELS

A *test level* is the spectrum of the shock or vibration environment that is specified for testing purposes, i.e., the spectrum given in a final test specification. The determination of a test level based upon a computed zone limit requires the selection of a value for β, the fraction of the locations within a zone where the spectra of the shock and/or vibration responses of the system structure will be exceeded by the zone (tolerance) limit. This selection is often made somewhat arbitrarily, with values in the range $0.90 \leq \beta \leq 0.99$ being the most common for acceptance and qualification tests. However, the value of β used to arrive at a test level can be optimized based upon an assessment of the adverse consequences (the potential cost) of an undertest versus an overtest. Also, even with an optimum selection, modifications to the test level may be required to account for the interactions of the equipment and the system structure and other considerations.

Optimum Test Level Selection. A number of procedures have been developed[8] that yield an optimum test level for equipment in terms of a percentile of the environmental distribution (which is essentially the value of β for a tolerance limit) as a function of a "cost" ratio C_T/C_F, where C_T is the cost of a test failure and C_F is the cost of a service failure. Some of the procedures assume the equipment being tested has already been manufactured in quantity, raising the possibility that a test failure will lead to refurbishing costs, while others account for a safety factor in the equipment design or a *test factor* based upon the assumed strength of the item being tested. The simplest test level selection rule, which applies to the acceptance testing of a single item of equipment, is given by[3]

$$\beta = \frac{1}{1 + (C_T/C_F)} \tag{20.5}$$

As an illustration, consider an item of equipment where a failure during test could be corrected by a relatively simple replacement of an inexpensive component, but a failure during service would be catastrophic, perhaps resulting in personal injury. According to Eq. (20.5), the item should be tested to a very severe level relative to the measured or predicted shock and/or vibration environment so as to sharply minimize the risk of an undertest; for example, if a service failure is assessed to be 1000 times as costly as a test failure, $\beta = 0.999$. On the other hand, consider an item where a failure in test would lead to a difficult and expensive redesign, but a failure during service would not be catastrophic. According to Eq. (20.5), the test level now should be moderate relative to the measured or predicted shock and/or vibration environment so as to minimize the risk of an overtest; for example, if a service failure is assessed to be only 9 times as costly as a test failure, then $\beta = 0.90$. Note that the selection procedure does not require the determination of quantitative costs in dollars, but only relative costs, which can be interpreted in qualitative terms. This allows such factors as the consequences of a possible delivery delay caused by a test failure or customer dissatisfaction caused by a service failure to be considered. Also, the conservatism of the test level can be further increased or decreased by selecting a larger or smaller value of γ for the tolerance limit computation.

Equipment-Structure Interactions. Test levels are commonly specified in terms of a motion parameter, for example, g^2/Hz versus frequency for a random vibration test. However, at the resonance frequencies of relatively heavy items of equipment, the apparent mass of the equipment dramatically increases, causing the equipment to behave like a dynamic vibration absorber on the system structure to which the equipment is mounted (see Chap. 6). If the test machine is made to deliver the specified motion to the equipment at its resonance frequencies, a severe overtest may occur. This problem is sometimes addressed by placing limits on the response of the equipment or by allowing "notches" in the specified test spectrum to be introduced at the frequencies of strong resonances of the equipment. The best approach, however, is to derive a second spectrum for the limiting force at the mounting points of the equipment and establish criteria for a dual control test that limits both the input force and the input motion to the equipment.[9]

Added Test Level Factors. For qualification tests where the item of equipment being tested will not be used in service, it is common to add a factor (often referred to as a *test margin*) to the derived test levels to arrive at a final specified test level. Such factors are usually justified to account for uncertainties not considered in the determination of the test levels, such as unknown variabilities in the equipment strength or its possible service use. These factors are sometimes selected rather arbitrarily, with typical values ranging from 3 to 6 dB above the derived zone limits.

SELECTION OF VIBRATION TEST DURATIONS

The *test duration* for a vibration test is the total time the excitation is applied to the equipment at its mounting points by the test machine. In some cases, the test duration is not relevant to the purpose of the test, for example, a development test. In many cases, however, an appropriate simulation of the total duration of the vibration environment anticipated in service is an important part of the test criteria. This is particularly true of qualification and statistical reliability tests, where the purpose is to detect design inadequacies that may lead to failures of any type during exposure to the service vibration environment, including "wearout" failures. For shock environments, this means exposing the equipment to repeated simulations of all the shocks anticipated during its service life, which can usually be accomplished in a reasonable period of time. For vibration environments, however, this means exposing the equipment to a simulation of the anticipated service vibration environment for a duration equivalent to the service life of the equipment, which may be thousands of hours. Vibration environments usually vary widely in overall level and perhaps spectral content during the equipment service life, for example, equipment on an automobile or truck in normal service use. As noted earlier in this chapter, statistical reliability tests are sometimes performed with a duration similar to the anticipated service life of the equipment. For qualification tests, however, it is usual to compress a long, time-varying service environment into a stationary test level of much shorter duration.[10] To do this, the following steps are required:

1. Assume a time-dependent failure model for the equipment
2. Compress the time-varying magnitudes of the environment into a single test level corresponding to a conservative estimate of the maximum magnitude of the environment
3. In some cases, increase the test level beyond the maximum magnitude of the environment to further accelerate the test

FAILURE MODELS

A *failure* of an item of equipment is defined as any deterioration of performance or any damage or malfunction that prevents the equipment from accomplishing its intended purpose. There are two basic types of failures that may be caused by vibration:

1. *Hard failure.* A failure involving permanent physical damage that makes the equipment unable to perform its intended purpose, even after the vibration is terminated. Hard failures generally result in observable damage, such as the fracture of a structural element or the permanent disability of an electronic element.
2. *Soft failure.* A failure involving a malfunction or deterioration of performance during the vibration exposure that makes the equipment unable to accomplish its intended purpose, but after the vibration is terminated, the equipment does not reveal any damage and functions properly. Soft failures most commonly occur in electrical, electronic, and/or optical elements, although soft failures may occasionally occur in complex mechanical elements, such as gyroscopic devices.

A *failure mechanism* is the specific means by which an item of equipment is damaged by exposure to an environment. All failure mechanisms are a function of the magnitude of the vibration exposure. A *time-dependent failure mechanism* is a function of both the magnitude and the duration of the vibration exposure. Soft failures during exposure to a vibration environment are rarely time-dependent, i.e., they usually occur immediately at the start of the vibration exposure. On the other hand, hard failures usually are time-dependent, although there are some exceptions. For example, if a vibration environment produces stresses that exceed the ultimate strength of a critical element in the equipment, a fracture will occur immediately at the start of the vibration exposure. See Chaps. 34 and 41 for further discussions of equipment failures.

To establish appropriate test durations for qualification vibration tests, only time-dependent failure mechanisms (usually producing hard failures) are of interest. Common examples of time-dependent failure mechanisms for equipment exposed to vibration environments are fatigue damage, force contact wear, relative velocity wear, and the loosening of bolts or rivets. A *failure model* is an analytical relationship between the time-to-failure of the equipment during exposure to a vibration environment and the magnitude of the vibration environment. For a wide class of time-dependent failure mechanisms, the time-to-failure τ for a stationary vibration excitation can be approximated by the *inverse power law*[10] given by

$$\tau = c\,\sigma^{-b} \tag{20.6}$$

where σ is the stress in the equipment caused by the vibration (or any measure of the vibration magnitude that is linearly related to stress), and b and c are constants related to the specific failure mechanism. From Chap. 34, if the endurance limit is ignored, the fatigue endurance curves for common metals fit the form of Eq. (20.6).

Using Eq. (20.6) and assuming a vibration test is performed that accurately simulates the basic characteristics (for example, random versus periodic) and the spectrum of a service vibration environment, the time required to produce a similar amount of damage in the test environment T_t and the time in the service environment T_e are related by

$$T_t = \left(\frac{\sigma_e}{\sigma_t}\right)^b T_e \tag{20.7}$$

where σ is the rms value of the vibration, and the subscripts t and e denote the test and service environments, respectively. For random vibrations defined in terms of power spectra (i.e., $W(f)$ defined in Chap. 22), Eq. (20.7) becomes

$$T_t = \left(\frac{W_e(f)}{W_t(f)}\right)^{b/2} T_e \tag{20.8}$$

The value of the power b in Eqs. (20.7) and (20.8) varies widely for different failure mechanisms. For metal fatigue damage, a value of $b = 8$ is reasonable for many common materials (see Fig. 34.4) and is recommended in Ref. 3. However, a value of $b = 4$ is usually more appropriate for the typical failure mechanisms in electrical and electronic equipment.[11]

COMPRESSING TIME-VARYING SERVICE ENVIRONMENTS

For those vibration environments that vary substantially in severity during the equipment service life, the duration of the environment can often be reduced for testing purposes by using Eq. (20.7) to scale the less severe vibration levels to the most severe levels that occur during the service life. Such scaling procedures are most applicable to environments that vary in overall level but not substantially in spectral content. For

TABLE 20.4 Determination of Equivalent Duration for Automobile Equipment Vibration Environment

Type of road segment	Duration on road segment, hours	rms vibration on road segment, g	Equivalent duration on road segment A, hours
A. Unpaved secondary roads	40	3	40
B. Improved secondary roads	460	1.4	22
C. Primary roads	1500	0.9	12
D. Major highways	2000	0.7	6
Total equivalent duration on road segment A (hours)			80

example, consider an item of electrical equipment designed for a motor vehicle with a service life of 4000 hours. Assume the anticipated service vibration environment for the vehicle at the equipment mounting points has the rms values summarized in Table 20.4. Further assume $b = 4$ in Eq. (20.7), and the vibrations during the various service conditions have a similar spectral content. Table 20.4 indicates the damage potential of the 4000-hour service vibration environment can be simulated by a vibration test with a duration of 80 hours at the maximum service vibration level.

For those vibration environments where the spectral content and the overall levels change during service operations, the test duration computations illustrated in Table 20.4 must be made on a frequency-by-frequency basis using Eq. (20.8) or a similar expression for the appropriate spectral description in Table 20.2. This will result in a different test duration at each frequency, leading to two possible testing options: (1) a series of tests, each covering a different frequency range with a different test duration or (2) a single test with a test duration equal to the longest test duration computed at any frequency. The second option is usually the more practical and assures a conservative test.

ACCELERATED TESTS

An *accelerated test* is a test where the test duration is reduced by increasing the test level in a manner that will maintain the same environment-induced damage to the equipment. The determination of a test duration for a stationary vibration test that produces the same damage as a nonstationary vibration environment, as detailed in the preceding section, constitutes the most desirable form of accelerated testing because the test level never exceeds the maximum vibration level that the equipment will experience during its service environment. Furthermore, most of the damage experienced by equipment in service usually occurs during exposure to the maximum vibration level in the service environment, which typically covers a small fraction of the total service duration (see Table 20.4). In such cases, reducing the relatively long durations of the less severe vibrations by scaling to the maximum level according to Eq. (20.7) does not introduce a major error, even if the exponent in Eq. (20.7) is inaccurate.

Highly Accelerated Tests. Situations often arise where scaling the less severe segments of a nonstationary vibration environment to a stationary vibration level corresponding to the maximum level of the environment may yield a test duration that is still too long to be practical; for example, the test duration of 80 hours computed for the 4000-hour service environment in Table 20.4 may still be too long for testing purposes. In such a case, it is common to further reduce the test duration by increasing the test level beyond the maximum level the equipment will experience during its anticipated service environment. Indeed, if no limit is placed on the rms test level in Eq. (20.7), the test duration theoretically can be made as short as desired, provided the ultimate strength of the equipment structure is not exceeded. However, increasing the test level beyond the maximum level during the anticipated service environment introduces major uncertainties in the test results, particularly if the equipment is fabricated using different materials and/or incorporates electrical, electronic, and/or optical elements. The problem is that the failure mechanisms of some elements may not comply with the inverse power law in Eq. (20.6). Furthermore, even if all failure mechanisms do comply with Eq. (20.6), the exponent b may vary from one element to another within the equipment. Hence, increasing the test level to accelerate the test rapidly in compliance with Eq. (20.7) may cause some elements of the equipment to be undertested and others to be overtested. The result could be the occurrence of unrepresentative failures during the accelerated test.[11]

Durability and Functional Tests. A common procedure to suppress unrepresentative failures that may be caused by rapidly accelerating a vibration test of equipment with a long service life is to perform two separate tests, namely, a durability test and a functional test. A *durability test* is intended to reveal only time-dependent failures and is rapidly accelerated to produce the same damage as the entire duration of the service vibration environment based upon a specific damage model, for example, Eq. (20.7). The equipment is not required to function during the durability test, and any failures that are not time-dependent are ignored. A *functional test* is intended to reveal failures that are not time-dependent (i.e., failures related only to the vibration level) and is not accelerated with test levels that exceed the maximum expected vibration level during the service environment. The equipment is required to function during the test, but since the failures of interest are not time-dependent, the test duration is not critical; for example, the test duration is often fixed by the time required to fully operate the equipment and verify that it properly performs its intended purpose.

SHOCK AND VIBRATION TESTING

The laboratory machinery used to perform vibration tests and shock tests are detailed in Chaps. 25 and 26, respectively. In all cases, there are several issues that must be carefully considered in performing such tests, the most important being:

1. Identification of test failures
2. Type of excitation to be used
3. Single versus multiple-axis excitation
4. Test fixtures

IDENTIFICATION OF TEST FAILURES

In all shock and vibration tests of equipment, it is important to carefully establish what types of equipment malfunctions or anomalies will be considered failures. This determination depends heavily on the purpose of the test and sometimes on the judgment of the purchaser of the equipment. Here are a few examples:

1. Since a qualification test is intended to identify design problems, failures during the test that are clearly due to workmanship errors or material defects are usually ignored, i.e., the equipment is repaired and the test is continued.
2. Since the test level for a highly accelerated qualification test is based upon a specific failure model, failures during the test that are not consistent with the failure model should be carefully evaluated and ignored if they are determined to involve a failure mechanism that is not time-dependent.
3. During durability tests of equipment, if a fatigue crack forms in the equipment structure that does not propagate to a fracture, whether the fatigue crack constitutes a failure or the length of the fatigue crack that constitutes a failure must be specified.
4. During functional tests of electrical, electronic, and/or optical equipment, if there is measurable deterioration in the performance of the equipment during the test, the exact degree of deterioration that prevents the equipment from performing its intended purpose must be specified.

TYPES OF EXCITATION

Shock tests are sometimes performed using specified test machines, but more often are performed using more general test machines that can produce transients with a desired shock response spectrum (see Chaps. 26 and 27). Although vibration environments may be simulated by mounting the equipment in a prototype system and reproducing the actual environment for the system, it is more common to apply the vibration directly to the equipment mounting points using vibration testing machines described in Chap. 25.

Random Tests. Random excitations are used to simulate random vibration in those tests where an accurate representation of the environment is desired, specifically, qualification, reliability, and some acceptance tests. The most commonly used random test machines produce a near-Gaussian vibration. If the actual environment is random but not Gaussian, a Gaussian simulation is acceptable since the response of the equipment exposed to the environment will be near-Gaussian at its resonance frequencies, assuming the equipment response is linear; this is because equipment resonances constitute narrow-band filtering operations that suppress deviations from the Gaussian form in the vibration response of the equipment.[12]

Sine Wave Tests. Sine wave excitations are used to simulate the fixed-frequency periodic vibrations produced by constant-speed rotating machines and reciprocating engines. Sine wave excitations are sometimes superimposed on random excitations for those situations where the service vibration environment involves both. Sine wave excitations fixed sequentially at the resonance frequencies of an equipment item (often referred to as a *dwell sine test*) are sometimes used in development tests, as well as in durability tests, to evaluate the fatigue resistance of the equipment.

Swept Sine Wave Tests. Sweep sine wave excitations are produced by continuously varying the frequency of a sine wave in a linear or logarithmic manner. Such excitations are used to simulate the vibration environments produced by variablespeed rotating machines and reciprocating engines. The usual approach is to make the sweep rate sufficiently slow to allow the equipment being tested to reach a near-full (steady-state) response as the swept sine wave excitation passes through each resonance frequency. Swept sine wave excitations are also used for development tests to identify resonance frequencies and sometimes to estimate frequency response functions (see Chap. 21).

MULTIPLE-AXIS EXCITATIONS

Shock and vibration environments are typically multiple-axial, i.e., the excitations occur simultaneously along all three orthogonal axes of the equipment. Multiple-axis shock and vibration test facilities are often used to simulate low-frequency shock and vibration environments, generally below 50 Hz, such as earthquake motions (see Chap. 24). Also, multiple-axis vibration test facilities have been developed for higher-frequency vibration excitations (up to 2000 Hz), but it is more common to perform shock and vibration tests using machines that apply the excitation sequentially along one axis at a time, i.e., machines that deliver rectilinear motion only (see Chaps. 25 and 26). Single-axis testing introduces an additional uncertainty of unknown magnitude in the accuracy of the test simulation, but there is debate as to whether the removal of this uncertainty justifies the high cost and complexity of multiple-axis test facilities.

TEST FIXTURES

A *test fixture* is a special structure that allows the test item to be attached to the table of a shock or vibration test machine. Test fixtures are required for almost all shock and vibration tests of equipment because the mounting hole locations on the equipment and the test machine table do not correspond. For the usual case where the test machine generates rectilinear motion normal to the table surface, a test fixture is also necessary to reorient the equipment relative to the table so that vibratory motion can be delivered along the lateral axes of the equipment, i.e., the axes parallel to the plane of the equipment mounting points. This requires a versatile test fixture between the table and the equipment, or perhaps three different test fixtures. If the direction of gravity is important to the equipment, the test machine must be rotated from vertical to horizontal, or vice-versa, to meet the test conditions.

For equipment that is small relative to the test machine table, L-shaped test fixtures with side gussets are commonly used to deliver excitation along the lateral axes of the equipment as illustrated Fig. 20.2. Unless designed with great care, such fixtures are likely to have resonances in the test frequency range. In principle, the consequent spectral peaks and valleys due to fixture resonances can be flattened out by electronic equalization of the test machine table motion (see Chap. 27), but this is difficult if the damping of the fixture is low. The best approach is to design the fixture to have, if possible, no resonances in the test frequency range.

For equipment that is large relative to the test machine table, excitation along the lateral axes of the equipment is commonly achieved by mounting the equipment on a horizontal plate driven by the test machine rotated into the horizontal plane, where the plate is separated from the flat opposing surface of a massive block by an oil film or hydrostatic oil bearings as shown in Fig. 20.3. The oil film or hydrostatic bearings provide little shearing restraint but give great stiffness normal to the surface, the stiffness being distributed uniformly over the complete horizontal area.

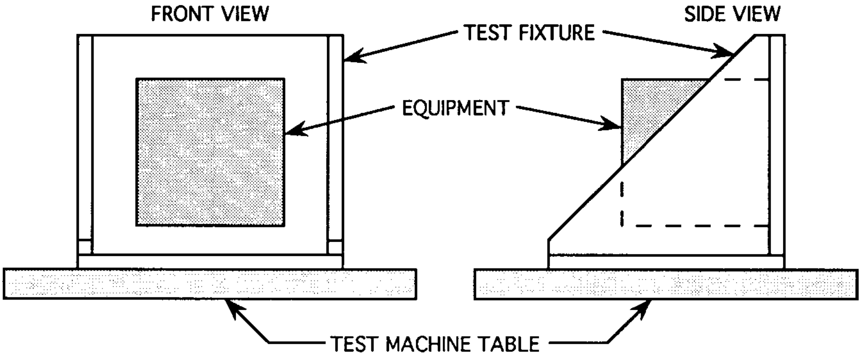

FIGURE 20.2 Test fixture to deliver excitation in the plane of the equipment mounting points.

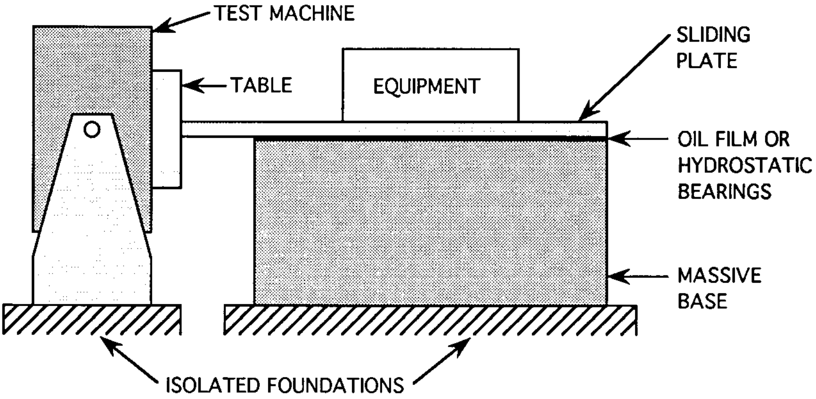

FIGURE 20.3 Horizontal plate to deliver excitation in the plane of the equipment mounting points.

Accordingly, a relatively light moving plate can be vibrated that has the properties of the massive rigid block in the direction normal to its plane. See Ref. 13 for further discussions of vibration and shock test fixturing.

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