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A Research Program for Seismic Qualification of Nuclear Plant Electrical and Mechanical Equipment

Task 2: Correlation of Methodologies for Seismic Qualification Tests of Nuclear Plant Equipment

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Prepared for
U.S. Nuclear Regulatory
Commission

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ABSTRACT

A general methodology has been developed for correlating the severity of one seismic qualification motion of given dynamic characteristics to another motion that may be of very different dynamic characteristics. Its most important application lies in the determination of whether equipment previously qualified to earlier, simpler standards are also qualified to newer, more complex standards. The methodology may also be used to obtain fragility information about equipment for its own purposes and use.

The approach developed includes the use of a vibrational equivalence concept, which allows a damage comparison between two different motions. The comparison is in terms of a damage fragility ratio D_{FR}, which is a ratio of incurred damage to that which the specific equipment item is capable of sustaining at its fragility level. Measurement of the damage at both levels can be in terms of response spectrum, power spectrum, or a variety of other parameters which may be used, or have been used in typical equipment qualification procedures. Relationships among the various parameters are defined, so that transformations from one to another are possible. The inherent use of the fragility function for the methodology causes some problem in that such data are not generally included in previous qualifiation information. This problem is overcome by defining a lower bound, or acceptable approximate fragility function, which is based on the previous qualification levels. If a correlation based on the approximate function is unsuccessful, then more accurate fragility data must be established before the severity comparison can be made with certainty. In this event, conduct of a completely new requalification program may be more practical.

A method of measuring relative damage severity of two motions is also developed in terms of a relative damage severity ratio D_{SR}. This ratio is shown to be proportional to several other relative severity factors that have previously been established by other researchers. It is shown that these parameters cannot be used for an absolute severity comparison, as can the damage fragility ratio D_{FR}.

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This report represents one of a series which is to present the results of a research program that is being conducted to evaluate methodology of equipment seismic qualification for nuclear plants. The overall program consists of the following subtasks:

1.1, 1.2, 1.3	Review methodology, aging, and static loads; Identify anomalies
1.4	Evaluate multiple frequency excitations
1.5	Consider combined dynamic environments
1.6	Develop in-situ test criteria
1.7	Study procedures for line mounted items
1.8	Publish Task 1 Summary Report
2.1, 2.2, 2.3	Investigate response level and multiple-parameter correlations
2.4, 2.5	Consider single parameter and damge severity factor correlations
2.6	Develop general correlation method
2.7	Publish Task 2 Summary Report
3.1	Recommend updating of qualification criteria
3.2	Publish Task 3 Summary Report
4.1, 4.2	Compile fragility data
4.3	Evaluate and reduce data
4.4	Publish Task 4 Summary Report

Specifically, this document constitutes the Task 2 Summary Report. Other reports previously published under Task 1 are listed as References 1 and 5 on the list given at the end of this report. Work on the other tasks is in progress, and will be reported in the later-indicated summary reports.

PRINCIPLE NOTATION

$\bar{a}_x$, $\bar{a}_y$	RMS acceleration at excitation x and response y
a_x^*, a_y^*	Peak acceleration values at excitation x and response y
B_e	Effective bandwidth of analysis
$B_{xy}(f)$	Base to elevated position structural transfer function
b_X, b_F	Peak/RMS ratio for signal x and for fragility function signal
D	Damage severity factor (Eq. 2-7)
D_{AR}	Damage amplification ratio (Eq. 2-8)
D_{FR}	Damage fragility ratio (Eq. 2-3)
D_{SR}	Relative damage severity ratio (Eq. 2-10)
$D_{xy}(f)$	Damage function (Eq. 2-9)
$F_{xy}(f,t)$	Fragility surface function
f	Frequency, Hz
f_c	Center frequency for limited excitation band
f_i, f_1, f_2	Specific frequencies
f_n, f_r	Natural frequency for mode n and mode r
$G_x(f)$, $G_y(f)$	Power spectral densities for excitation x and response y
$G_{ox}(f)$	Normalized excitation power spectral density (Eq. 1-5)
$G_{XF}(f)$	Power spectral density fragility function
G_o	Value of $G_{XF}(f)$ at $f = f_o$
g	Standard acceleration of gravity
$H_{xy}(f)$	Linear transfer of function of response at y to excitation at x
$H_{xy}(f_r)$	Value of transfer function for response at y due to excitation at x at natural frequency for mode r
$H^s_{xy}(f)$	Transfer function for simple oscillator (Eqs. 3-8 and 3-11)
I_A	Arias earthquake intensity factor (Eq. 2-6)
I_H	Housner spectrum intensity (Eq. 2-5)
k	Index indicating multiple time history samples
M(f,t)	Magnitude of actual excitation function
$M(f_1,t_1)$	Magnitude of actual excitation function at frequency f_1 and time t_1
$M_F(f,t)$	Magnitude of excitation at fragility surface (i.e., magnitude of fragility surface or function)

R	Aggregate peak response spectrum value for multiple modes (Eqs. 4-1 through 4-8)
R_I	Peak response spectrum values for mode I (Eqs. 4-1 to 4-6 and 4-8)
R_{OJ}, R_{KJ}	Peak response spectrum values for modes OJ and KJ (Eq. 4-5)
$R_x(f)$	Response spectrum at frequency f
$R_{XF}(f)$	Fragility response spectrum at frequency f
$R_a(f_r)$	Acceleration response spectrum at frequency f_r
$R_v(\beta,f)$	Pseudo-relative velocity response spectrum
T_k	Time duration of transient history k
t	Time
t_0, t_1, t_i	Specific times
$X_R(f)$	RMS amplitude of sine wave or narrow band random excitation
$X_{RF}(f)$	RMS amplitude sine wave or narrow band random fragility funtion
X_{RO}	Reference value of $X_{RF}(f)$
$X_{PF}(f)$	Peak amplitude sine wave or narrow band random fragility function
$\ddot{X}$	Peak amplitude of steady state sine acceleration excitation
$\ddot{X}_o$	Reference value of $\ddot{X}$
$\ddot{Y}$	Peak amplitude of steady state sine acceleration response
$\ddot{Y}_c$	Critical value of steady state sine acceleration response
y^*	Peak value of response at some location
y_r^*	Peak value of response in mode r at some location
α	Correction factor to account for multimode response (Eq. 4-9)
β	Damping ratio for general system
β_r	Damping ratio for mode r for general system
γ_r	Mode participation factor for mode r (Eq. 1-3)
$\phi_r(y)$	Value of rth mode eigenvector at point y
ζ	Damping ratio for simple oscillator

1.0 INTRODUCTION

1.1 Overview

Over the years, a variety of methods have been employed in seismic qualification tests which have included several different types of motion simulation [1]. Generally, test input motions have progressed from simple sine dwells or sweeps to more complex, but more realistic random motion earthquake simulations. As a result, it is often desirable to be able to compare the results of an earlier qualification test, which included the use of one type of excitation, with the requirements of a newer specification, to assure that the previous test was conservative. The purpose of this study is to establish a sound engineering basis by which seismic test motions can be compared, and to provide practical demonstrations of the results applied to typical nuclear equipment qualification problems. Inherently, such a comparative procedure falls under the category of vibration equivalence, and will be developed in detail by means of this general concept. However, our approach will necessarily include the concepts of fragility as well, and we therefore first consider an overall view of what we seek to accomplish in order to set the stage for subsequent details.

1.2 Vibration Equivalence Concepts

The use of vibration equivalence techniques for a variety of engineering applications has been described by Fackler [2], Curtis [3], and summarized in Reference [1]. Typically, equivalences can be established between vibration excitations that are either like (i.e., sine waves of different amplitudes and frequencies) or unlike (sine waves and random) in character. In these references, equivalences have been based on such typical parameters as peak responses, RMS (root mean square) response, energy dissipation, material fatigue, and other physical concepts that could be related to a postulated failure mechanism. In the qualification of nuclear plant equipment, a great variety of physical failure mechanisms may occur. Therefore, for this purpose, the concept of vibration equivalence will be generalized to include an arbitrary type of failure or malfunction, that can always be established by input vibrational conditions denoted as the fragility levels. It is understood that the failure or malfunction may or may not impart permanent damage to the equipment.

A conceptual approach for applying vibration equivalence to equipment qualification test methodology correlations is shown in Figure 1.2-1. The upper and lower halves of the diagram (Conditions 1 and 2, respectively) each represent the independent establishment of a fragility, or threshold of failure, level in an arbitrary specimen, which is subject to a dynamic excitation at location x. As indicated, the specimen may include elastic, inertial, and dissipative characteristics which are inherent in the transfer function $H_{xy}(f)$ for dynamic response at location y to excitation at point x. It is also understood that both the excitation and response are classified according to orthogonal spatial coordinates. The effect of the response at location y is to actuate a failure mechanism which exists at that point in the specimen. This arbitrary failure mechanism is dependent on the response amplitude at location y, and may also be dependent on time. Thus, the failure is indirectly dependent on the excitation amplitude, frequency, and time. If the excitation is manipulated so that failure barely occurs, then the threshold of failure, or fragility function $F_{xy}(f,t)$ is generated. This function represents a surface, any point on which corresponds to failure of the specimen. If more than one physical failure mechanism at more than one response point is present, then each posseses a failure surface, and the minimum value composite failure surface becomes of concern. Hence, the minimum fragility surface or function can always be established by adjustment of the excitation amplitude, frequency, and time. It should also be note. that the level of the fragility surface can be influenced by the defin..ion of failure. For example failure of a relay can either be defined as a loss of contact of the normally closed side, or as loss of cont... the normally closed and contact of the normally open side. Each definition may result in a different fragility function. In the cases to be considered it is assumed that a definition of failure has been established and it is consistent between the two excitation types.

The central assumption of the vibration equivalence concept can now be postulated: the establishment of failure conditions [i.e., various points $F_{xy}(f_1,t_1)$ and $F_{xy}(f_2,t_2)$ corresponding respectively to the excitation -1 and excitation -2 conditions] is possible by various types of vibration

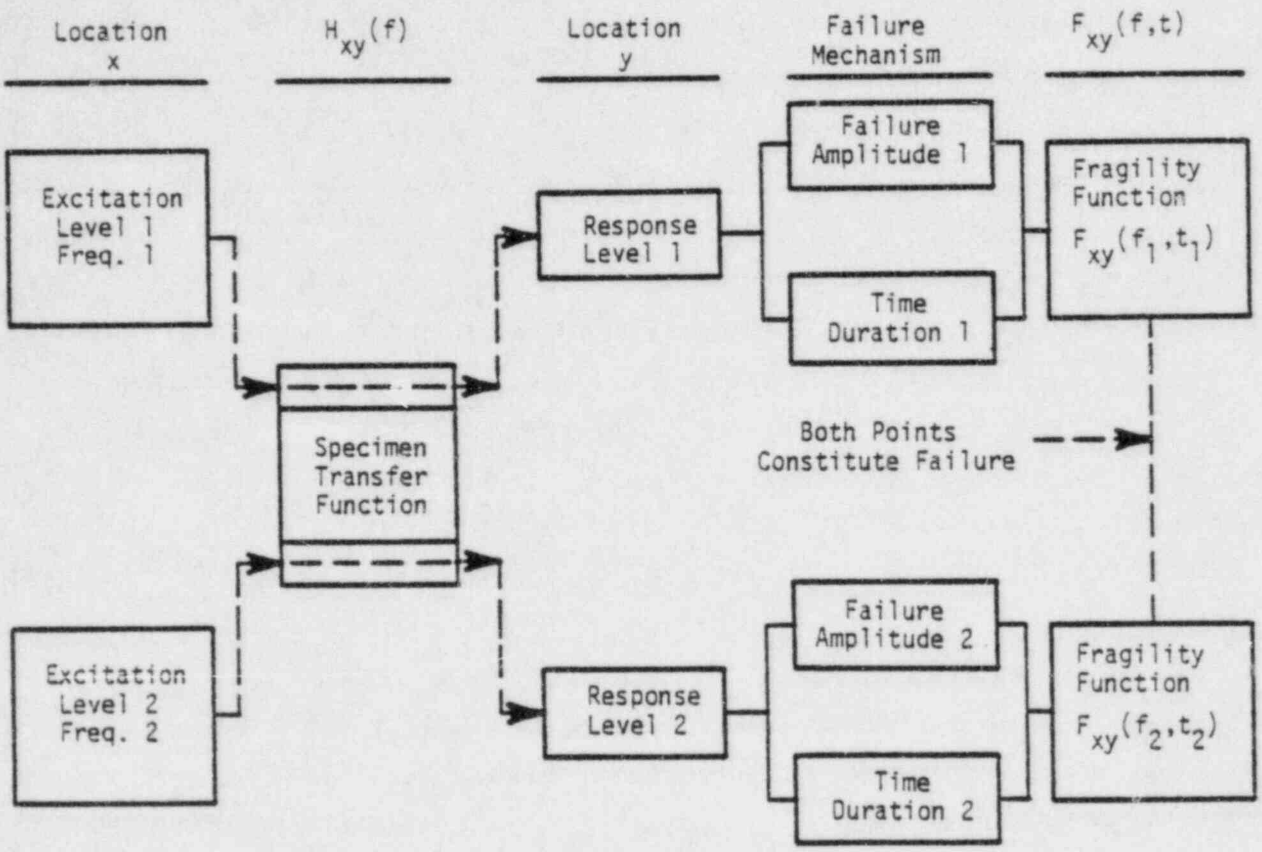


Figure 1.2-1 Conceptual Approach to Vibration Correlation

excitations, and the corresponding amplitudes, frequencies, and time durations constitute equivalent excitations.

The above general approach will be developed in detail for application to the seismic qualification problem. However, the parameters by which amplitudes, frequencies, and time durations are measured must be appropriate for the specific application. Therefore, we first consider some general response relationships which will be useful in the development.

1.3 Dynamic Response Relationships

Considering either the upper or the lower half of the diagram in Figure 1.2-1, we may write various relationships between the dynamic response at location y and the excitation x, so long as we assume the existence of a linear transfer function $H_{xy}(f)$.

Specifically, if one considers the use of modal analysis [4] applied to earthquake transient conditions, the peak response y_r^* at some point y of a structure due to response in mode r can be related to the excitation at some point x by the expression

$$y_r^* = 2\,\beta_r \,|\, H_{xy}(f_r) \,|\, R_a(f_r) \qquad (1\text{-}1)$$

where β_r is the damping ratio for mode r, $H_{xy}(f_r)$ is the value for the linear transfer function for the response at y due to the input at x at the natural frequency f_r when computed for a damping ratio of β_r. $R_a(f_r)$ is the response spectrum value at frequency f_r. If several widely spaced modes are present, the total response at y can be estimated by a square root of the sum of the squares (SRSS) of the contribution of the response in each mode:

$$y^* = \{\sum_r [2\,\beta_r \,|\, H_{xy}(f_r) \,|\, R_a(f_r)]^2\}^{1/2} \quad . \qquad (1\text{-}2)$$

The above relationships are written in terms of the value of the rth mode transfer function $H_{xy}(f_r)$. This is a form that is especially useful for experimental measurement. However, the relationships are equally valid for analysis, although in that case the rth mode participation factor γ_r is usually utilized instead of the transfer function. The two are related by:

$$\gamma_r = \frac{2\beta_r}{\phi_r(y)} \left| H_{xy}(f_r) \right| \qquad (1\text{-}3)$$

where $\phi_r(y)$ is the magnitude of the rth mode eigenvector evaluated at point y.

It must be noted that only the peak value of the response is predicted by the above relationships. In order to predict a complete response spectrum at point y a time history solution of the structural equations may be performed, and then a response spectrum computed from the response time history at point y. This approach is rather tedious, and is no longer necessary if a power spectral density approach is used [5,6], whereby a direct transformation between response spectrum and power spectral density (PSD) is effected.

If the use of random processes is considered, a relationship between the response power spectral density $G_y(f)$ at point y and the excitation power spectral density $G_x(f)$ at point x of a linear system subject to a stationary random process can be expressed as [7]:

$$G_y(f) = \left| H_{xy}(f) \right|^2 G_x(f) \qquad (1\text{-}4)$$

or

$$G_y(f) = \left| H_{xy}(f) \right|^2 G_{ox}(f)\bar{a}_x^{\,2} \qquad (1\text{-}5)$$

where $G_{ox}(f)$ is a normalized PSD and $\bar{a}_x$ is the time averaged RMS value of the excitation during the strong motion of an earthquake. The power spectra $G_y(f)$ and $G_x(f)$ also are time averaged during the strong motion, and can be considered to be approximately stationary during that period [5]. Thus, $\bar{a}_x$ can also be considered to be approximately stationary.

Equation (1-5) can be integrated over frequency to obtain

$$\bar{a}_y^{\,2} = \bar{a}_x^{\,2} \int_0^\infty \left| H_{xy}(f) \right|^2 G_{ox}(f)\,df \qquad (1\text{-}6)$$

or

$$\bar{a}_y^{\,2}/\bar{a}_x^{\,2} = A_{xy}^{\,2} = \int_0^\infty |H_{xy}(f)|^2 \, G_{ox}(f)df. \qquad (1\text{-}7)$$

The latter expression will be especially useful in later developments.

2.0 GENERALIZED FAILURE CONCEPTS

2.1 Fragility and Functionality

As was indicated in the INTRODUCTION, a measure of fragility is recognized to include a determination of the level of specific excitation parameters (amplitude, frequency, time) at which failure, or malfunction, occurs in a specimen. However, this information is not usually required as part of an equipment qualification process. On the other hand, functionality of a specimen at specified excitation levels is required for qualification, and accordingly is well documented for any test. Fragility and functionality are very much related, although they are basically different concepts. In effect, fragility is the upper limit of functionality. Conversely, existing qualification data, which include excitation levels and functionality data, may be useful as a lower bound for fragility. Thus, since fragility data are necessary for a general application of the vibration equivalence concept, use of such existing qualification data, where possible, is highly desirable to avoid the necessity of generating large volumes of more precise fragility information for the great variety of equipment typically contained in a nuclear plant.

One of the most general descriptions of a fragility concept has been discussed by Roundtree and Safford [8], and is shown in Figure 2.1-1 as a fragility surface. Note that the surface can be represented as the function

$$F_{xy}(f,t) = M_F(f,t) \qquad (2\text{-}1)$$

where $M_F(f,t)$ is the magnitude or amplitude of the excitation at the fragility surface. Note also, as indicated above, that the true surface may be quite complex, depending on mechanical resonances in the specimen, but a simpler lower bound surface can be defined conservatively acceptable for practical engineering purposes. Furthermore, this surface may be assumed to be independent of time for many types of equipment, so that Equation (2-1) reduces to the fragility function:

$$F_{xy}(f) = M_F(f) \ . \qquad (2\text{-}2)$$

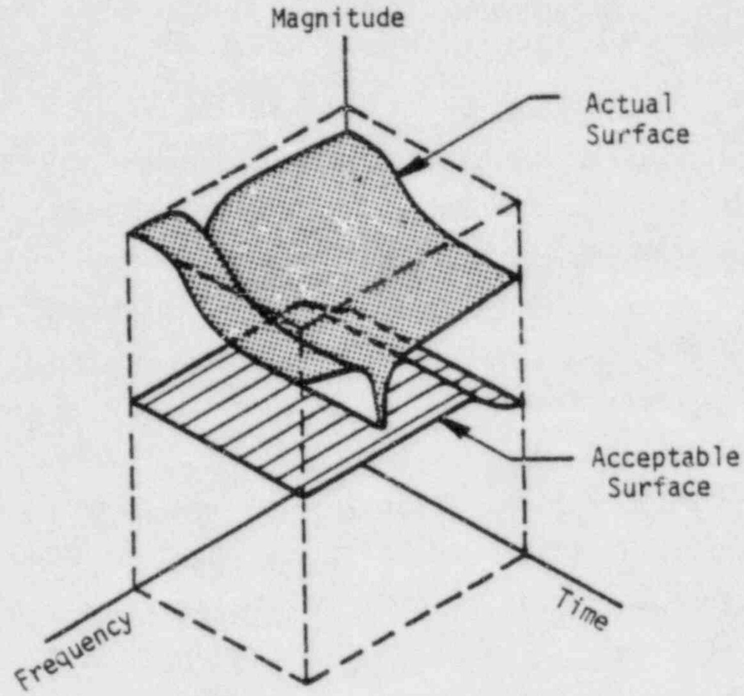


Figure 2.1-1 Comparison of Actual with Acceptable Fragility Surface

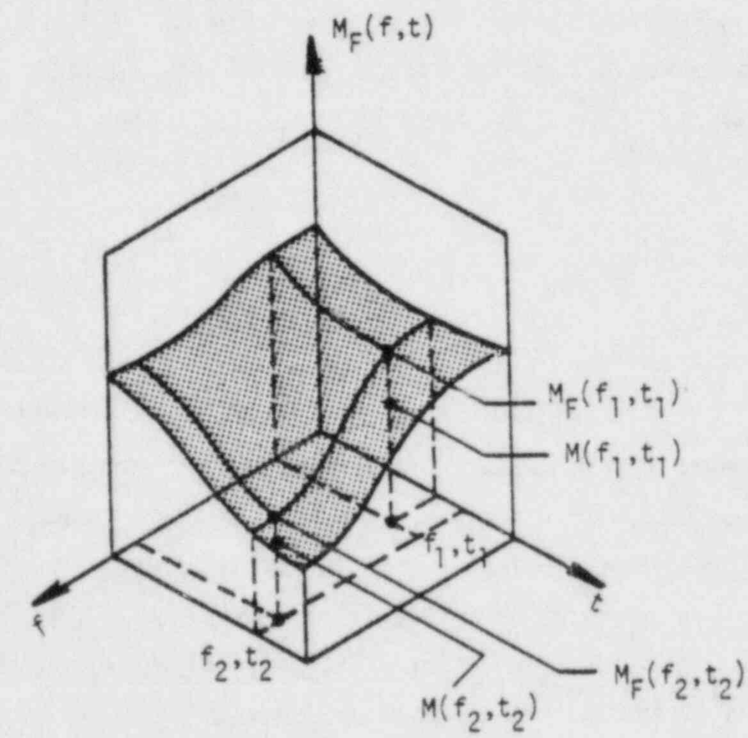


Figure 2.1-2 Basis for Damage Fragility Ratio

In other cases only amplitude may be significant, and the surface reduces to a point on the magnitude axis.

A convenient method of measuring the onset of fragility is in terms of the damage fragility ratio defined as

$$D_{FR} = \frac{M(f,t)}{M_F(f,t)} \leq 1 \tag{2-3}$$

where $M(f,t)$ is the value of the actual excitation function and $M_F(f,t)$ is the value of the fragility function at the same conditions of frequency and time. A specific example of this type of relationship is typically used for measure of fatigue damage accumulation, where the functions are based on the Minor Criterion [9], or some other fatigue damage accumulation theory. A conceptual interpretation of Equation (2-3) is shown in Figure 2.1-2, where the functions $M(f,t)$ and $M_F(f,t)$ are plotted for two sets of frequency and time conditions. A damage fragility equivalence similar to that described in Figure 1.2-1 can now be stated as

$$M(f_1,t_1)/M_F(f_1,t_1) = M(f_2,t_2)/M_F(f_2,t_2) \tag{2-4}$$

This will be the general basis for comparing various test motions.

2.2 Fragility Function Parameters

The appropriate parameter for measure of magnitude of a fragility function $M_F(f,t)$ for nuclear plant equipment is very important to the problem at hand. Generally, the parameter appropriate for a specific case is dependent on the type of failure that occurs. A summary of available data on equipment fragility has been given by Kennedy, et al [10]. This list of data is repeated in Section 9.0 of Reference [.]. The parameter assumed to be most important for fragility is listed for each category of equipment. Generally, spectral acceleration (or ZPA) is given as magnitude with frequency distribution understood. Although time is not listed, it must be included for some items (i.e., those susceptible to material fatigue, wear, etc.).

The list of fragility parameters given by Kennedy is acknowledged to be only a best guess of values, with only minimal data available for support. On the other hand, it is imperative to use these data to the best advantage for the problem at hand. It is therefore appropriate to consider several types of fragility parameters that may be used, the relationship among them, and how the Kennedy data falls under a special category. Figures 2.1-3 and 2.1-4 give more details of certain types of fragility functions to aid in this consideration.

Bandwidth dependent fragility functions are shown in Figure 2.1-3. The bandwidth of measurement for such functions must be considered carefully for correct resolution. If the function is independent of time, then the RRS function $R_{XF}(f)$ or PSD function $G_{XF}(f)$ is the ordinary type used for many qualification procedures. Note that both these functions must be plotted to the same analysis (resolution) bandwidth B_e, in order to be comparable. The indicated sample curves qualitatively represent PSD functions $G_{XF}(f)$ for excitations of four different total bandwidths but each with the same RMS amplitude value. Again, the analysis bandwidth for each curve B_e must be the same. Further, note that the PSD value for the sine wave is finite, since B_e is a finite value. Finally, it should again be emphasized that a direct transformation between PSD and RRS is possible, so that either parameter can be used interchangeably.

For certain types of failure, the exact narrow frequency bandwidth is of lesser importance, (although the center frequency for the narrow band may be important) and a fragility function of the type shown in Figure 2.1-4 results. Here, the RMS amplitude, $X_{RF}(f)$, is recognized to be the square root of the area under the PSD curve, as given in Figure 2.1-3. The single RMS value given in Figure 2.1-4 in effect is the transformation of all the four curves in Figure 2.1-3, since they all have the same center frequency f_c. Thus, the bandwidth independent fragility function still depends on center frequency, but not on the bandwidth of the excitation energy for bandwidths up to approximately 10 Hz, which includes earthquake type ground motions [6]. If peak amplitude is important in a given problem, then the peak/RMS ratio must be considered carefully for the different types of narrow band excitations.

2.2.1 Threshold Failures

Some components suffer damage when a given peak value of input to them is exceeded, no matter what its frequency content. That is, their

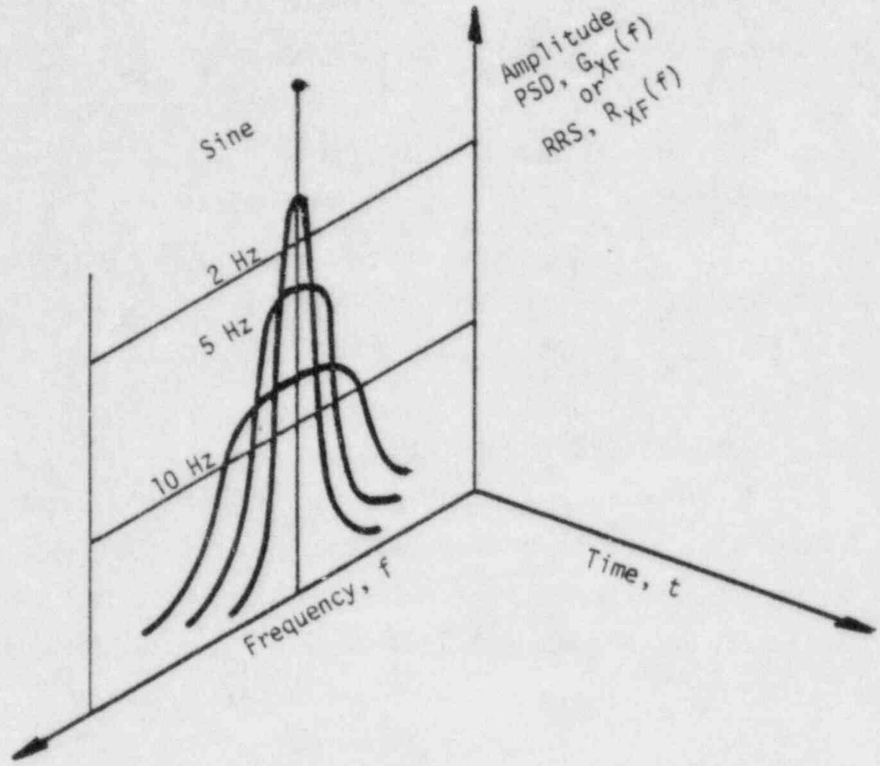


Figure 2.1-3 Bandwidth Dependent Fragility Function

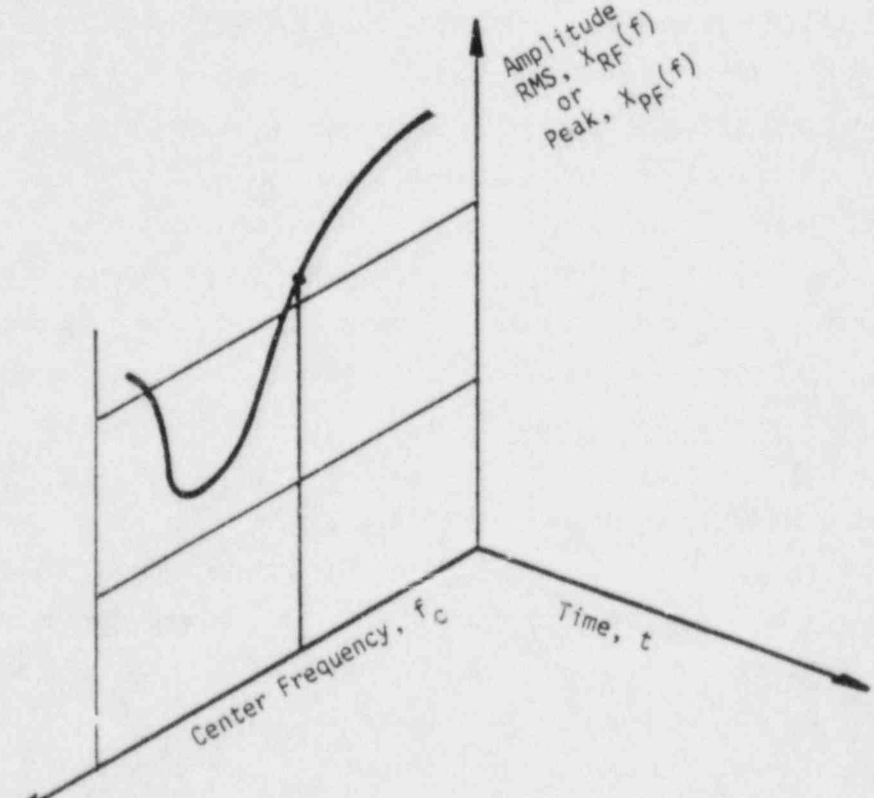


Figure 2.1-4 Bandwidth Independent Fragility Function

fragility surface in Figure 2.1-4 reduces to a horizontal line in the peak amplitude/ frequency plane. Ultimate stress, critical interference, etc., are examples when they occur in bodies that are essentially rigid in the frequency range of interest. A comparison of test severity in this simple case requires that the peak excitation acceleration is equivalent, regardless of the type of input motion. In other cases the RMS acceleration magnitude may be the only parameter of concern. Here also, the fragility surface reduces to a horizontal line in the RMS amplitude/frequency plane.

2.2.2 Amplitude/Frequency Failures

Many components suffer failure when the excitation level associated with a certain frequency exceeds a certain value. Chatter of relays and excessive response at natural frequencies in all types of structures and fucntional mechanisms fit into this category. The manner in which the frequency content of the excitation matches with the critical frequencies in the component is of primary importance. The failure surface of Figure 2.1-2 reduces to a curve in the amplitude/frequency plane in this case (corresponding to Equation 2-2), with minimum points at the critical resonance frequencies. The exact form of the curve depends on how the fragility function is established. One approach is to establish a failure region in the plane by exciting the device with increasing levels of steady state sinusoidal excitation at various frequencies and noting the levels at which failure occurs (obviously nondestructive failure is assumed for obtaining multiple points). Such a procedure tacitly assumes that failure does not occur from interaction of multiple modes present. The fragility curve may also be established by similarly exciting the device with successive narrow bands of random energy. In this case the bandwidth must be sufficiently narrow to resolve any minima in the curve. For cases where multiple mode interaction does occur, the curve must be established with increasing incremental bandwidths of random energy. In the worst case the fragility can only be established with the entire frequency content present in an anticipated excitation. In any event, response spectrum or PSD, are parameters applicable to this case. Specific examples of the use of both will be given later. Although time is not explicitly included for these cases, it is implicitly included in the computation of response spectrum and power spectrum.

2.2.3 Cumulative Damage Failures

This category requires all three parameters to define the fragility surface. Material fatigue, wearout, and in some cases operational malfunctions such as galling, fretting, or chatter appear to be sensitive to frequency content, sustained vibration level, and time. Fragility surfaces still may be developed with narrow band frequency excitations provided that multimode interaction does not enter the process. A measure of the fragility surface is related to a classical stress-cycle (S-N) diagram for steady state sine excitation. On the other hand RMS amplitude of a narrow band random excitation of given center frequency (as in Figure 2.1-4) may also be used. Intermediate stages of damage at levels less than the fatigue limit can also be calculated by appropriate equivalent damage theories [9].

2.2.4 Integrated Parameters for Similar Motions

The various parameters discussed in paragraphs 2.2.1-2.2.3 may be used ultimately for comparing the absolute damage severity of dissimilar motions. On the other hand, for the existence of certain similar dynamic conditions, several so-called earthquake intensity factors have been postulated for measurement of relative severity. Nevertheless, these parameters are also usable for measurement of fragility primarily for cases where proportional response will occur in a specimen. Practically, this means that the frequency content of the parameter is always understood to be similar for the cases that are compared. Computation of severity level for various earthquake time histories at ground level would be a typical example. In this case, a single number relative ranking of test severities can be established by use of one of these parameters. Furthermore, its value for the level at fragility also allows a correlation of the numbers with absolute damage by means of a direct ratio, similar to Equations (2-3) or (2-4).

Spectrum intensity for earthquake-type motions has been defined by Housner [11] as

$$L_H = \int_{f_o}^{f_i} R_v(\beta, f)\, df \qquad (2\text{-}5)$$

where $R_v(\beta,f)$ is the pseudo-relative velocity response spectrum for the given transient. The integral is carried out over the range of frequencies for which input motion exists, i.e., in the frequency plane for the response spectrum $R_x(f)$ in Figure 2.1-3. The fragility level results for $R_v(\beta,f) = R_{vF}(\beta,f)$.

Earthquake intensity has been defined by Arias [12] as

$$I_A = \frac{\pi}{2g} \int_0^{t_0} a_x^2 (t)\, dt. \tag{2-6}$$

It is intended to indicate the energy dissipated by a structure subject to the acceleration transient $a_x(t)$. Since the integral is proportional to time average mean squared acceleration, the effects of sustained vibration and time are included. This parameter corresponds to a value of $X_R^2(f)$ in the amplitude/frequency plane of Figure 2.1-4.

Damage severity factor has been defined by Kana [13], and includes the product of peak excitation, RMS level, and time;

$$D = \sum_k a_k^* \bar{a}_k T_k \tag{2-7}$$

where a^* is peak acceleration input, $\bar{a}$ is time average acceleration, and T_k is time duration. A summation over k different test runs is included. This parameter may be used to represent fragility as a function of all three axes in Figure 2.1-4. Under certain conditions it is proportional to the Arias Intensity factor, as will be shown later.

2.3 Measurement of Relative Severity

2.3.1 General Concept

The use of the damage fragility ratio defined in Equations (2-3) and (2-4) allows a direct measure of absolute damage or fragility that occurs for a given set of excitation conditions. This relationship will be instrumental in the direct use of the vibrational equivalence concept for comparing the absolute damage effectiveness of various test motions for causing failure in a given specimen. However, there is also utility in providing a measure of the relative severity of different types of motions. One such parameter has been considered in the past, and will be further developed into an additional parameter that is related to fragility. It must be emphasized that the relative severity parameters do not give a direct measure of whether or not failures actually occur. As mentioned before, that information is obtained by use of expressions such as Equation (2-3). However, the utility of the relative severity parameter is to give a quick indication of the severity level of one type of motion relative to another, when applied to a given specimen.

2.3.2 Integrated Parameter for Dissimilar Motions

The parameters defined by Equations (2-5), (2-6), and (2-7) cannot be used directly to compare relative severities of motions whose frequency content is radically different. Further development is necessary to allow for the interaction of the excitation frequencies with the natural modes of the component. Such development has been performed for the damage severity factor given by Equation (2-7). The ratio of response damage severity to excitation damage severity, or damage amplification ratio is given as

$$D_{AR} = \frac{\sum_k a^*_{ky} \bar{a}_{ky} T_{ky}}{\sum_k a^*_{kx} \bar{a}_{kx} T_{kx}} . \tag{2-8}$$

Examples of this amplification ratio are given in Reference [13] for several different types of excitation waveforms.

The above damage amplification ratio bears no direct relationship to a fragility surface. However, with some additional development, a parameter related to the fragility of a specific item can readily be defined. We consider the case of equipment that is subject to amplitude/frequency failures as described in paragraph 2.2.2. The fragility function for this case is given by Equation (2-2). We now further define a damage function $D_{xy}(f)$ as

$$D_{xy}(f) = [F_{xy}(f)]^{-1} . \tag{2-9}$$

We further specify that the units on $D_{xy}(f)$ be arranged to be nondimensional, and that for the various fragility parameters defined in Section 2.2 we have

$$F_{xy}(f) \equiv X_{RF}(f) \text{ or } X_{PF}(f) \text{ or } [G_{XF}(f)B_e]^{1/2}$$

for use in Equation (2-9). Thus, the form of this function is that of a damage transfer function, with peaks occurring at each resonance. However, the amplitude levels all correspond to that of the fragility curve for each respective frequency. Therefore, this damage transfer function $D_{xy}(f)$ is related to $H_{xy}(f)$ identified in Figure 1.2-1, but also includes the influence of the failure mechanism present. Nevertheless, by analogy we may further define a damage severity ratio D_{SR} based on the use of Equation (1-7) as

$$D_{SR} = (\bar{a}_y/\bar{a}_x)_F = \left[\int_0^\infty |D_{xy}(f)|^2 \, G_{ox}(f)df \right]^{1/2} . \qquad (2\text{-}10)$$

This parameter now includes the effects of frequency, both of the fragility curve for a given specimen and the excitation. The excitation is expressed in terms of the PSD for the most general form. However, if the excitation is in the form of a sine dwell at frequency f_1, then Equation (2-10) reduces to

$$D_{SR} = |D_{xy}(f_1)| . \qquad (2\text{-}11)$$

Equation (2-10) is directly related to the Arias Intensity Factor (Equation 2-6) through the definition of a mean square acceleration. It is also directly related to the damage amplification ratio in Equation (2-8), for those cases where peak/RMS ratios in responses are equal to those of excitations. More of this will be covered in the next section.

Equation (2-10) can now be used directly to compare the response effects in any given specimen for any type of test waveform whose power spectrum $G_x(f)$ is computed. The latter computation can be readily performed by standard laboratory real time, or FFT analyzers. The fragility function $F_{xy}(f)$ and therefore the damage function $D_{xy}(f)$ can either be developed analytically or measured directly. Thus, Equation (2-10) appears to be especially useful for comparing the relative severity of broadband tests with any other type of simulations that have sometimes been used as a representation of ground level motion. In fact, within limits to be developed, it can be used to compare relative severities of any type of simulation that has been used for qualification testing in the past.

3.0 TEST SEVERITY IN SIMPLE SYSTEMS

3.1 Determination of Fragility Function

The previous concepts will now be applied to the problem of test severity comparison or correlation in simple systems. For this purpose, a simple system is defined as a specimen whose fragility function is influenced by a single resonance, and therefore can be generated by a slowly swept sine or narrow band random excitation. Furthermore, the failure mechanism is independent of time, but may be dependent on excitation bandwidth. Therefore, we will initially consider the fragility function in the form of a PSD function $G_{XF}(f)$.

For a typical simple system, the PSD fragility funtion might look like Figure 3.1-1. This curve might be derived analytically, or it could be measured during a fragility test in which a narrow band excitation is employed. It represents the PSD excitation level $G_{XF}(f)$ at which failure occurs for a given excitation frequency. From a test, the curve may be generated by increasng a sine wave amplitude of fixed frequency until failure occurs, or by increasing the amplitude of a random input of narrow bandwidth B_e until failure occurs. In either case, the RMS amplitude value is measured, squared, and divided by the bandwidth B_e for the PSD value. The bandwidth B_e of random excitation must be sufficiently narrow to resolve the minimum point of the function, which occurs at the frequency of the single resonance of the device.

3.2 Damage Severity Relationships

With the PSD fragility function $G_{XF}(f)$ established, a criterion for failure can be postulated for any arbitrary excitation whose PSD is given as $G_x(f)$. That is, failure will occur if

$$G_x(f_i)/G_{XF}(f_i) \geq 1 \qquad (3\text{-}1)$$

at any frequency f_i (see Figure 3.1-1). Furthermore, vibration equivalence can be established by this ratio as a specific example of Equation (2-4).

Note that although the above measure of failure is based on PSD amplitude, for some specimens the first occurrence of a peak value may be appropriate. For such a case Equation (3-1) becomes

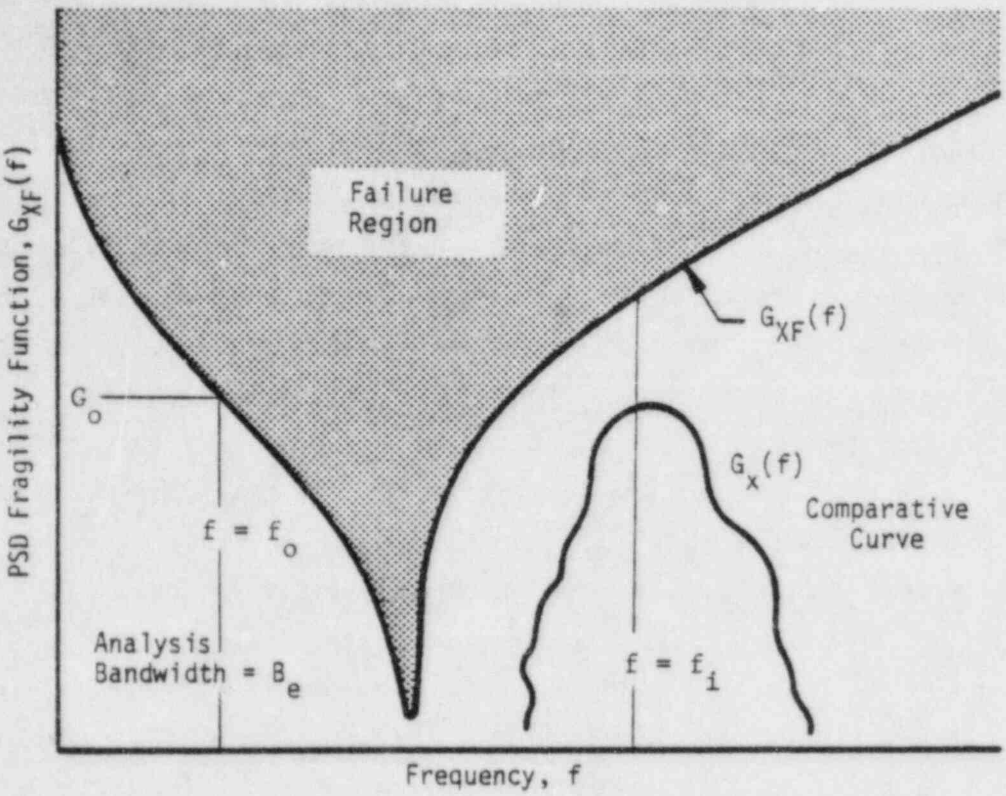


Figure 3.1-1 Fragility Function for Single Resonance Device

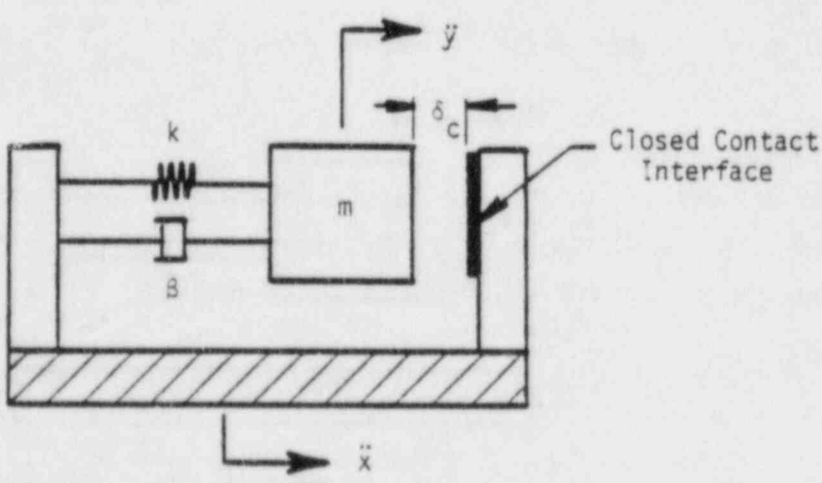


Figure 3.3-1 Simple Schematic of Normally Open Relay Contact

$$b_x[G_x(f)B_e]^{1/2}/b_F[G_{XF}(f)B_e]^{1/2} \geq 1 \qquad (3\text{-}2)$$

where b_x is the peak/RMS ratio for the signal which is compared, and b_F is the similar ratio for the signal with which the fragility curve was established. Values of this ratio for typical types of test time histories will be given in a later section.

The damage function $D_{xy}(f)$ for this case can now be defined by the use of Equation (2-9). Recall that this function is defined to be nondimensional. Therefore we can write

$$D_{xy}(f) = (G_oB_e)^{1/2}/[G_{XF}(f)B_e]^{1/2} \qquad (3\text{-}3)$$

where the function has been nondimensionalized by the PSD value G_o at frequency f_o. This process is arbitrary, so that the value at any convenient frequency could be used. For the simple system, by means of Equation (2-10) the damage severity can now be written as

$$D_{SR} = (\bar{a}_y/\bar{a}_x)_F = [\int_0^\infty |G_o/G_{XF}(f)| \; G_{ox}(f)df]^{1/2} \qquad (3\text{-}4)$$

for arbitrary inputs, and

$$D_{SR} = X_{RO}/X_{RF}(f) \qquad (3\text{-}5)$$

for sine wave excitation, where X_{RO} and $X_{RF}(f)$ are the respective sine wave RMS amplitudes at the reference frequency f_o and any frequency f.

3.3 Specific Example

Consider a specific example of the simple oscillator representation of the spring-loaded, normally open relay contact shown in Figure 3.3-1. The single degree-of-freedom spring-mass system represents a contact which is held normally open with a gap δ_c relative to the contact interface surface. At some critical acceleration $\ddot{y}_c$, the dynamic force on the mass will exceed the spring and damper force, and chatter of the relay will occur. We seek to develop the damage severity ratio relationships for this system.

Consider a steady state sine excitation of amplitude $\ddot{X}$ at each frequency, with increasing amplitude until $\ddot{Y}$ achieves the critical response value $\ddot{Y}_c$. Thus, the failure criterion is

$$\ddot{Y} = \ddot{Y}_c \tag{3-6}$$

and in this special case we may use the simpler parameter $X_{RF}(f)$. Hence, from linear vibration theory [14], the fragility function can be written as,

$$|\ddot{X}_{RF}(f)| = \ddot{Y}_c[H^s_{xy}(f)]^{-1} \tag{3-7}$$

where

$$|H^s_{xy}(f)| = |\ddot{Y}/\ddot{X}| = \left\{ \frac{1 + 4\zeta^2(f/f_n)^2}{[1-(f/f_n)^2]^2 + 4\zeta^2(f/f_n)^2} \right\}^{1/2} \tag{3-8}$$

where f_n is the oscillator natural frequency. From Equation (2-9) we may therefore write the damage function as

$$D_{xy}(f) = \frac{\ddot{X}_o}{\ddot{Y}_c} H^s_{xy}(f) \tag{3-9}$$

and from Equation (2-10) the damage severity ratio becomes

$$D_{SR} = (\bar{a}_y/\bar{a}_x)_c = \frac{\ddot{X}_o}{\ddot{Y}_c} \left[\int_o^\infty |H^s_{xy}(f)|^2 G_{ox}(f)df \right]^{1/2} . \tag{3-10}$$

Now note that for light damping (i.e., $\zeta \leq 0.1$) we may use the approximation

$$|H^s_{xy}(f)| \approx \left\{ \frac{1}{[1-(f/f_n)^2]^2 + 4\zeta^2(f/f_n)^2} \right\}^{1/2} \tag{3-11}$$

If we consider the case where the excitation power spectral density $G_x(f)$ is broad compared with $H^s_{xy}(f)$ (as indicated in Figure 3.3-2), then

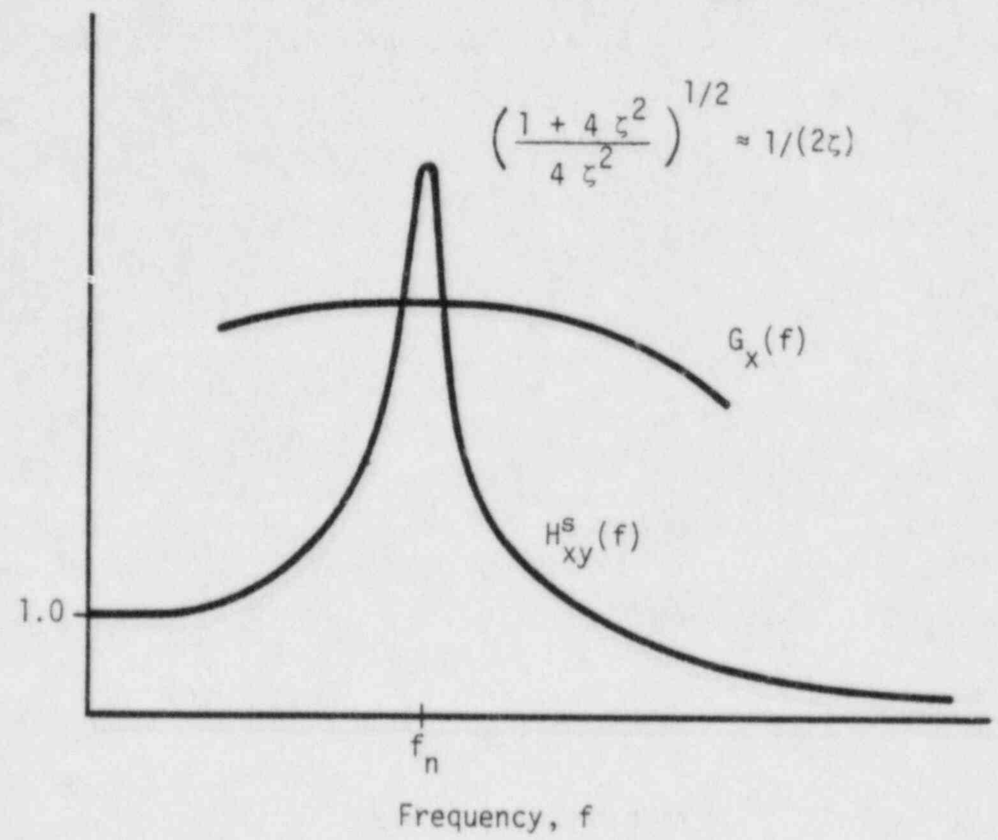


Figure 3.3-2 Relative Shapes of Damage Function and Excitation Power Spectral Density

upon substitution of Equation (3-11) into (3-10), and evaluating the integral as indicated in Thompson [14], the damage severity ratio for this case becomes

$$D_{SR} = \frac{\ddot{X}_o}{\ddot{Y}_c} \left[\frac{\pi f_n}{4\zeta} \; G_{ox}(f_n) \right]^{1/2} \qquad (3\text{-}12)$$

where $G_{ox}(f_n)$ is the value of the normalized excitation PSD at the natural frequency f_n. Since we may nondimensionalize by any convenient value of $\ddot{X}_o$, we let

$$\ddot{X}_o = \ddot{Y}_c$$

and therefore

$$D_{SR} = \left[\frac{\pi f_n}{4\zeta} \; G_{ox}(f_n) \right]^{1/2} . \qquad (3\text{-}13)$$

Finally, note that for a sine wave excitation of frequency f, from Equation (3-5) and $X_o/Y_c = 1$,

$$D_{SR} = \left| H^s_{xy}(f) \right| \qquad (3\text{-}14)$$

and for $f = f_n$ this becomes

$$D_{SR} = 1/(2\zeta) \; . \qquad (3\text{-}15)$$

3.4 Approximate Evaluations

Additional study of the relationships given in Section 3.2 shows that some very useful approximate evaluations can be performed for test time histories whose excitation of a linear system produces a response such that

$$a^*_x/\bar{a}_x = a^*_y/\bar{a}_y \; . \qquad (3\text{-}16)$$

That is, peak/RMS ratio for output equals that for the input. This relationship is known to exist for steady state sine excitation and also for stationary random excitation whose amplitude probability density is Gaussian or normal [15]. In order to check the validity of this relationship, various simulated earthquake and sine beat time histories were input to a linear analog computer oscillator circuit and characteristics of both excitation and response were studied. Peak/RMS amplitude ratios were measured for various oscillator natural frequencies and damping. The various excitation waveforms included some that had previously been recorded at the seismic simulator table level during earlier tests [5], and some that were analytically synthesized. The results are given in Table 3.1. Of course, the measurements were limited by the time duration of the signals as indicated.

The results for various test waveforms are given in Table 3.1A. From these data it was noted that the peak/RMS ratios for all types of signals tended to be higher for the inputs than for the outputs. Furthermore, the values for the simulated earthquake signals were significantly higher than 3.0, which would generally be an upper limit for a process with a Gaussian distribution. A closer inspection of the test excitation waveforms revealed that exaggerated peaks had been generated by mechanical nonlinearities (rattling and impacts) in the seismic table, specimen, or associated apparatus. This type of behavior for test simulations has been well documented by various experimentors [1]. Such behavior tended to reduce the validity of Equation (3-16). Therefore, additional data were generated from independently synthesized waveforms, which were also input to the analog oscillator circuit.

Table 3.1B shows results for an excitation signal taken directly from a standard stationary random noise generator. The frequency content was filtered to pass only 1 to 33 Hz energy. It can be seen that the peak/RMS ratios of both input and output are quite close. However, the values are also somewhat above 3.0. Thus, this noise source was also only approximately Gaussian in amplitude distribution.

Finally, a set of data was acquired from the oscillator circuit by inputting independent analytically synthesized waveforms. These data are given in Table 3.1C. The sine dwell data satisfies the peak/RMS ratio equivalence, as would be expected. The data for the R.G. 1.60 simulated

TABLE 3.1 PEAK/RMS RATIO FOR EXCITATION OF ANALOG OSCILLATOR

Excitation Waveform	Oscillator Frequency	Oscillator Damping	Full Event* Input	Full Event* Output	Strong Motion** Input	Strong Motion** Output
A. Test Waveforms						
10.6 Hz Sine	10.6	0.005	4.41	2.03	3.90	1.95
Beat	10.6	0.010	4.45	2.29	4.08	2.08
1 Beat Pause	10.6	0.020	4.30	2.64	4.18	2.39
	10.6	0.050	4.41	2.87	3.85	2.72
	10.6	0.100	4.10	3.01	4.17	3.18
NRC 001	10.0	0.005	5.00	3.64	4.18	2.99
Simulated	10.0	0.010	5.10	3.78	4.30	3.35
Earthquake	10.0	0.020	5.10	3.98	4.10	3.31
	10.0	0.050	4.91	3.96	4.45	3.46
	10.0	0.100	4.99	4.13	4.25	3.41
NRC 011	10.0	0.005	5.85	3.64	4.98	2.91
Simulated	10.0	0.010	5.77	4.11	4.74	3.42
Earthquake	10.0	0.020	5.94	4.42	4.98	3.56
	10.0	0.050	5.85	4.86	4.74	3.79
	10.0	0.100	6.00	4.31	4.84	3.59
B. Laboratory Noise Generator						
Stationary	10.0	0.005	3.93	3.46	----	----
Random	10.0	0.050	3.93	3.56	----	----
C. Analytically Synthesized Waveforms						
10.0 Hz Sine	10.0	0.01	1.42	1.41	----	----
Dwell	10.0	0.02	1.42	1.41	----	----
	10.0	0.05	1.43	1.41	----	----
	10.0	0.10	1.43	1.41	----	----
	10.5	0.02	1.43	1.41	----	----
10.0 Hz Sine Beat No Pause	10.0	0.02	1.99	1.63	----	----
10.0 Hz Sine	10.0	0.01	2.81	1.83	----	----
Beat	10.0	0.02	2.81	2.18	----	----
1 Beat Pause	10.0	0.05	2.80	2.58	----	----
	10.0	0.10	2.82	2.69	----	----
	10.5	0.02	2.78	2.29	----	----
10.0 Hz Sine Beat 2 Beat Pause	10.0	0.02	3.34	2.63	----	----
Reg Guide 1.60 Horizontal 2%	9.92	0.02	3.42	3.67	3.27	3.05

* For Analytically Developed Waveforms - 4 samples or 20 seconds.
For remainder - 16 samples or 34 seconds.

**For Analytically Developed Waveforms - 2 samples or 12 seconds.
For remainder - 8 samples or 18 seconds.

earthquake also satisfies the equivalence quite well. Note however that the ratios are still somewhat higher than 3.0. This results from the present definition of strong motion [5], which tends to include some effects of nonstationarity, and thereby reduces the RMS level, compared with results presented by some other researchers. The sine beat data appears to show reasonable equivalence only for $\zeta \geq 2\%$, and only for application of the sine beat exactly at the resonance frequency for the oscillator. Thus, under these conditions, the applicability of Equation (3-16) appears to be reasonable.

Therefore, when Equation (3-16) is assumed to be valid, the following development is possible for a general structure having only one mode present in the excitation frequency range. From Equation (2-10) we have

$$D_{SR} = (\bar{a}_y/\bar{a}_x)_F = [\int_0^\infty |D_{xy}(f)|^2 G_{ox}(f)df]^{1/2} \quad (3\text{-}17)$$

and with the use of Equation (1-1), for the single mode at $f = f_r$ we can write

$$a_y^*/a_x^* = 2\beta_r\, |D_{xy}(f_r)|\, R_a(f_r)/a_x^* \quad (3\text{-}18)$$

where we have also assumed that

$$H_{xy}(f_r) = D_{xy}(f_r). \quad (3\text{-}19)$$

This is equivalent to assuming that the damage mechanism is linearly proportional to the motion response at some point in the structure. In view of Equation (3-16), we may combine Equations (3-17) and (3-18) as

$$2\beta_r\, |D_{xy}(f_r)|\, R_a(f_r)/a_x^* = [\int_0^\infty |D_{xy}(f)|^2 G_{ox}(f)df]^{1/2}. \quad (3\text{-}20)$$

Now for a general structure having only one mode in the excitation frequency range and transfer function $H_{xy}(f)$ we can write

$$H_{xy}(f) = \gamma_r \phi_r(y)\, H_{xy}^s(f)$$

where $H^s_{xy}(f)$ is the simple oscillator transfer function given in Equation (3-11), and γ_r is the modal participation factor. Thus, from Equation (3-19) we have

$$D_{xy}(f_r) = \gamma_r \phi_r(y)/2\beta_r$$

which could also have been obtained directly from Equation (1-3). Finally, in view of Equation (3-17), Equation (3-20) reduces to

$$\gamma_r \phi_r(y)\ [R_a(f_r)/a^*_x] = [\int_0^\infty |D_{xy}(f)|^2\ G_{ox}(f)df]^{1/2} = D_{SR}\ . \qquad (3\text{-}21)$$

This result is extremely useful, as it indicates that the relative damage severity ratio integral for a general structure with only one dominant mode response is proportional to the response spectrum amplification ratio for a simple oscillator. Maximum values of this ratio are shown in Figure 3.4-1 for a variety of the signals listed in Table 3-1. By maximum value of the ratio, it is understood that the peak response spectrum ratio is taken from all possible values of the response spectrum, for a given excitation waveform. Thus, this ratio is a useful approximation of the relative damage severity ratio, for those cases where it is applicable, since it can readily be calculated from the usual data obtained in a qualification test. Curves of the type shown in Figure 3.4-1 have been used as an indication of damage severity in the past by Fischer [16] and Ibanez [17]. However, the limitation on their applicability has been heretofore unknown. We emphazise, of course, that for those cases where the validity of Equation (3-16) is in doubt or where more than one dominant mode of a structure is present, then the relative damage severity must be calculated by the more elaborate integral from Equation (3-17). Furthermore, even for the case of only one mode present, for any narrow band excitation such as sine dwell, sine beats, or even narrow band random, the excitation center frequency must exactly match that of the response spectrum calculation, or error occurs. The reduction of values for the test excitation sine beats compared with analytical excitation sine beats in Figure 3.4-1 demonstrates how a slight mismatch of resonance can alter results. Finally, to apply the results in Figure 3.4-1 to an actual structure having a single dominant mode, one must incorporate the amplification into Equation (1-1).

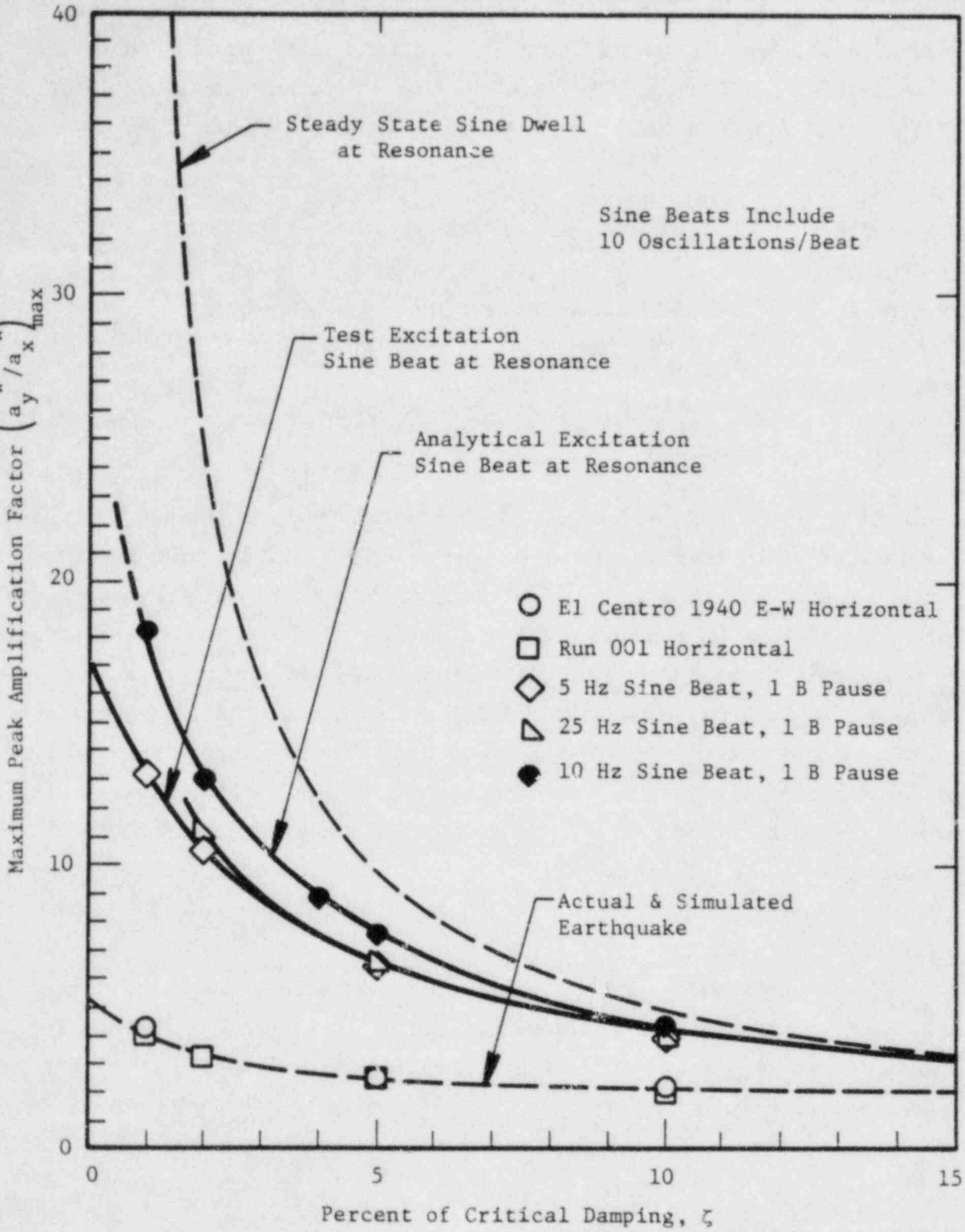


Figure 3.4-1 Maximum Peak Amplification Factors for a SDOF System Under Various Excitation Conditions

For the case of rather broad frequency excitations, such as near ground level, the results in Table 3.1 indicate that the peak/RMS ratio approximation is quite good. Therefore, by combining Equations (3-13) and (3-21) for a simple oscillator (i.e., $\gamma_r \phi_r(y) = 1$) we can write

$$R_a(f_r) a_x^* \simeq \left[\frac{\pi f_r}{4\zeta} G_{ox}(f_r) \right]^{1/2} . \tag{3-22}$$

In view of Equation (1-5) this becomes

$$G_x(f_r) \simeq \frac{4\zeta}{\pi f_r} \left(\frac{\bar{a}_x}{a_x^*} \right)^2 R_a^{\,2}(f_r) \tag{3-23}$$

which is a closed form approximation for transformation between PSD and response spectrum that is approximately valid for motions near ground level. A check of this equation with response spectra and PSD measurements made for all RG 1.60 runs in the previous work [5] indicated the degree of approximation present for those cases. Figure 3.4-3 shows an example where results calculated with Equation (3-23) are compared with a more accurate transformation of the response spectrum for the typical ground level run [5] shown in Figure 3.4-2. The differences in the results appear to be more attributable to nonsatisfaction of the conditions specified in Figure 3.3-2 rather than Equation (3-16). That is, the PSD of typical earthquake ground motion is not sufficiently flat to allow Equation (3-13) to be accurate.

Some further useful relationships between various fragility, intensity, and relative severity parameters can be developed for those cases where Equation (3-16) is approximately valid. From Equation (2-7) the damage severity factor D becomes

$$D = \sum_k \bar{a}_k^{\,2} \, T_k \left(\frac{a_k^*}{\bar{a}_k} \right)$$

and from Equation (2-6) we have

$$D = \frac{2g}{\pi} I_A \, b_x \tag{3-24}$$

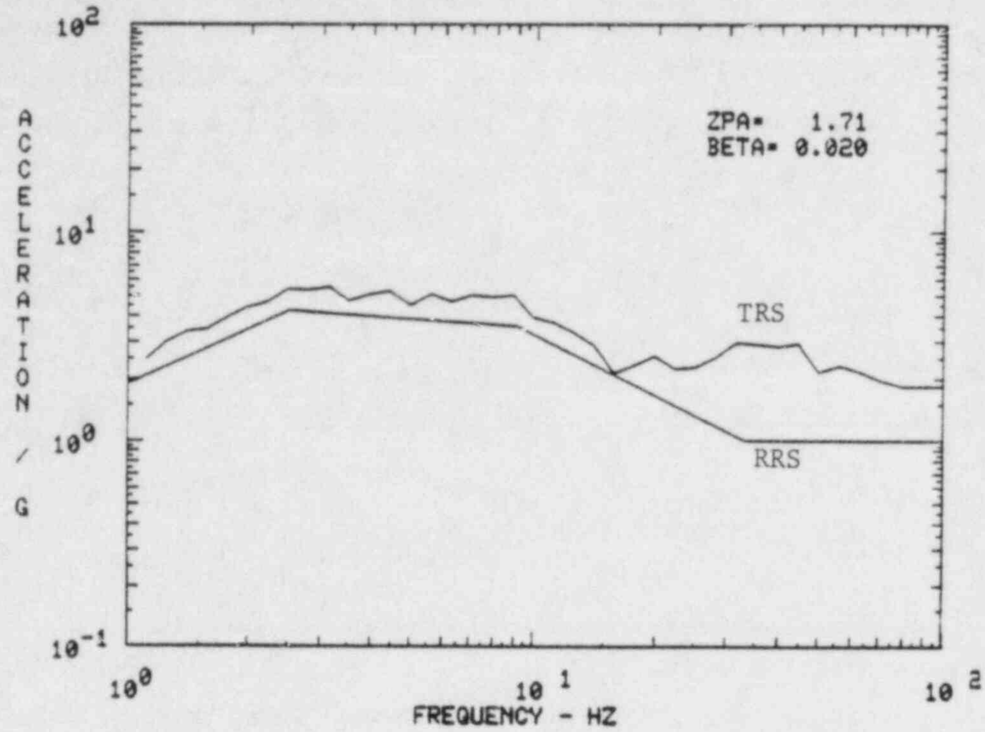


Figure 3.4-2 TRS Envelope of RRS for Run 001

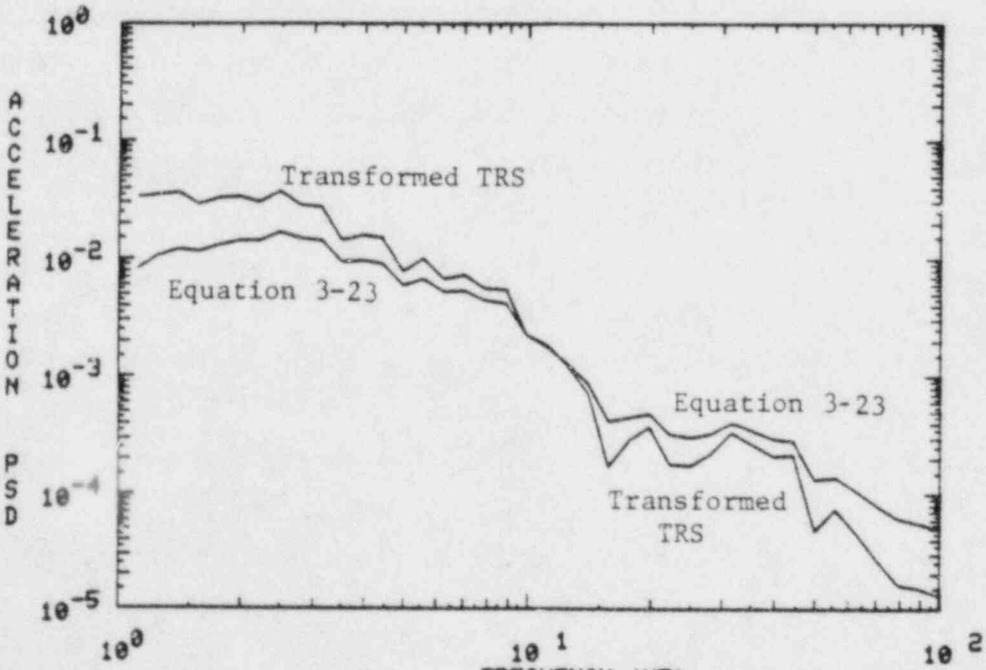


Figure 3.4-3 Transformed and Approximate (Equation 3-23) PSD for Run 001

a relationship between the damage severity factor and the Arias Intensity factor. Furthermore, in Equation (2-8) we let the time duration for input T_{kx} equal that for output T_{ky} and see that for this case the damage amplification ratio reduces to

$$D_{AR} = \bar{a}_y^2/\bar{a}_x^2 .$$

If the squared RMS values are assumed to be taken at the fragility excitation, then from Equation (2-10) we have

$$(D_{AR})_F = D_{SR}^{\;2} . \qquad (3\text{-}25)$$

3.5 Extension of Excitations

3.5.1 Multiaxis Excitation

Up to this point the development of a fragility surface (or function) has been assumed to be defined for a uniaxial excitation. On the other hand, typical excitations under earthquake conditions occur along three orthogonal axes in space. Thus, the relationship of the fragility surface to excitation along each of these axes may need to be considered. Two separate situations may exist:

1) The fragility surface for each axis exists independently of inputs along the other axes. In this case, the correlation problem can be approached for each axis independently as a uniaxial excitation, similar to the preceding discussions.
2) The fragility surface for each axis is dependent on interaction with excitation along the various axes (i.e., the principal axis of the response which causes failure is not aligned with any of the orthogonal axes of the excitation). In this case, a definition of the fragility surface must be obtained with simultaneous excitation along each axis. Obviously, this leads to a very complex problem, and its approximation by the previous case is very much in order, with appropriate judgement made as necessary.

3.5.2 Interface of Device with System

The conceptual hardware specimen depicted in Figure 1.2-1 is perfectly general, in that it may represent a single device or instrument, or it may also represent a complete system. Of course, the single resonance simple system whose fragility function would look like Figure 3.1-1 would probably represent a small item such as the normally closed relay previously analyzed. On the other hand, a complete system, such as an electrical cabinet, may have several resonances, with accompanying minima in its fragility functions. The question then becomes, if fragility functions are available only for devices, how is this information to be used to predict fragility in a cabinet on which the device is to be used? The answer lends itself well to the transfer function approach, providing that the fragility function is independent of time. That is, we assume that for the device we have

$$F^{D}_{xy}(f) = M(f)$$

and for the base to elevated position at which the device is to be mounted on a cabinet we have the transfer function $B_{xy}(f)$. The new fragility function relative to the system base becomes

$$F^{B}_{xy}(f) = M(f)/B_{xy}(f) \quad . \tag{3-26}$$

Such a fragility function would exist for each device mounted on the system, and the aggregate system fragility function would be given by the minimum envelope of all of the individual system fragility functions.

4.0 TEST SEVERITY IN COMPLEX SYSTEMS

4.1 Complex System Characteristics

To this point the development of the fragility function and its use in correlating test motions has dealt with simple systems. As defined previously a simple system is one whose fragility function is influenced by a single resonance. It now becomes necessary to extend the development to complex systems where several failure modes can occur as the result of multiaxis and/or multimode response, and interaction between responses is included. The key point is that interaction between the failure modes occurs. Thus, a multimode system may still be able to be treated as a simple system even if several well separated modes exist, or if the bandwidth of excitation is such that no interaction occurs. In this case the procedures outlined previously are applicable. Due to the difficulties involved when considering complex systems, it is advantageous to develop approximations as required to reduce the system to a simple one.

For the case where qualification was performed using broadband excitation the multimode response of the complex system has been accounted for in the testing procedure. It is only necessary to define the existing test response spectra or PSD as the fragility function and compare the new requirements to this level. On the other hand, it is anticipated that much present day equipment, which may fall under the category of complex systems, may also have previously been qualified only by single frequency excitation, such as a sine sweep. It is still desirable to be able to use such data to develop a lower bound fragility function for the equipment. However, it will be necessary to develop a procedure to modify the existing data, and apply a correction which will conservatively account for any modal interaction that may occur.

4.2 Approximate Lower Bound Fragility Function

Consider a complex system whose fragility function $G_{SF}(f)$ under sine wave excitation may result as shown in Figure 4.1-1. The indicated failure region without interaction must lie above a lower boundary which includes interaction caused by broad band excitation. We will establish an approximation for this lower boundary (i.e. the lower curve in Figure 4.1-1) by developing a correction factor α to be applied to the original data.

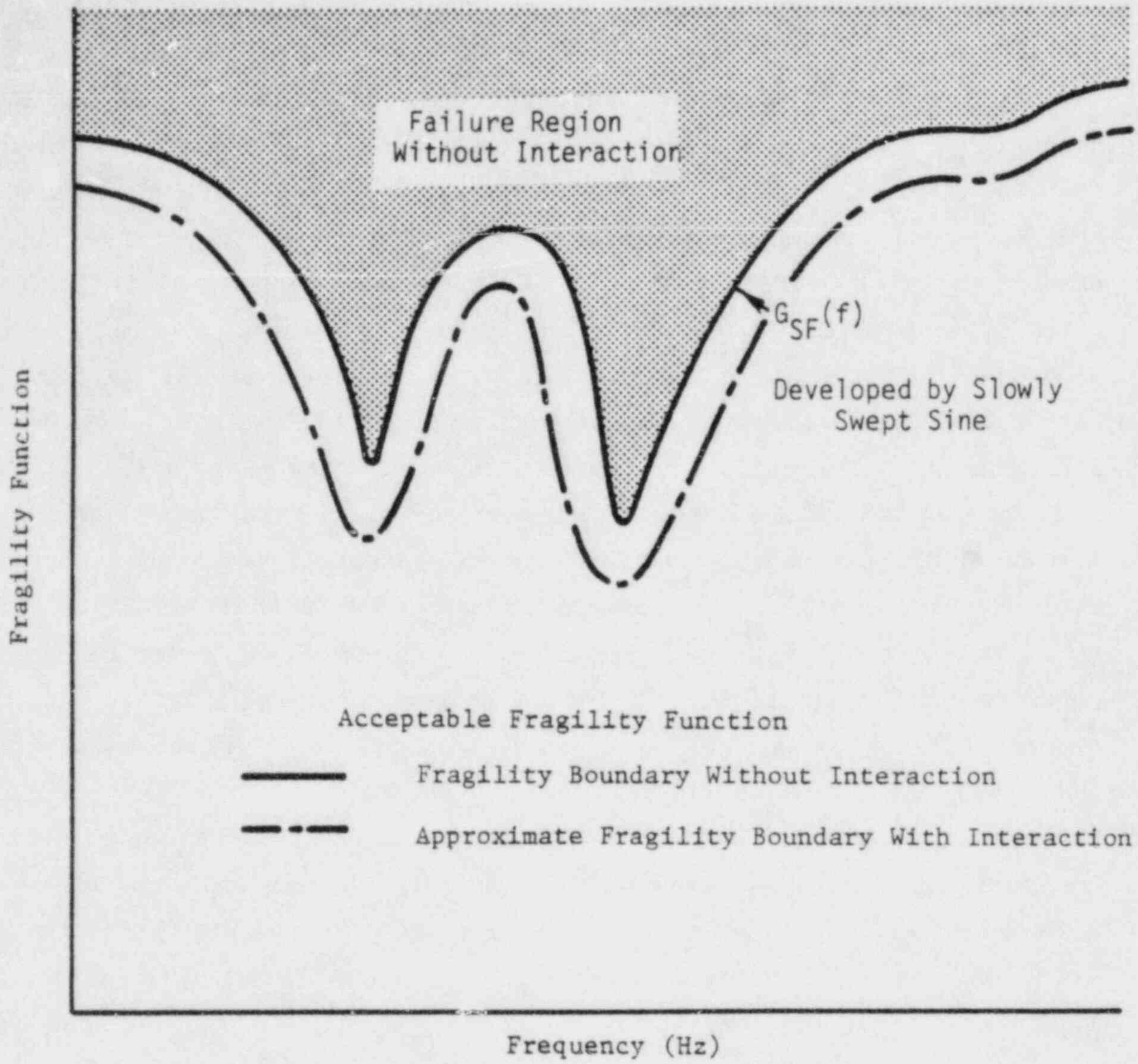


Figure 4.1-1 Development of Lower Bound Fragility Function for Complex Systems

It is the determination of this approximate, yet conservative level that is the subject of this section. Once this determination has been made, the previously described procedures for comparing absolute test severities in simple systems can be applied. The development will be based on the use of existing analytical methods for combining multimode responses.

A number of procedures have been developed in structural analysis to look at the combined effects of multiaxis and multimode response. Since the exact time histories of the excitation components for a future seismic event cannot be defined, these procedures generally are based on modal or response spectrum analysis. Furthermore, since it has been demonstrated that there is a transformation between the response spectrum and a PSD for a stationary random signal [6], these procedures also can be applied to a fragility surface defined either as a response spectrum or a PSD.

Various procedures have been suggested and comparisons made to a time history solution to account for multiaxes and multimode excitation response of structural systems [18-23]. The response spectrum procedures include:

1) Absolute Sum [20,22,23]

$$R = \sum_{I=1}^{N} R_I \qquad (4\text{-}1)$$

R = maximum response

N = number of axes/modes

R_I = peak response for each axis/mode

2) Square Root of the Sum of the Squares (SRSS) [18-23]

$$R = \sqrt{\sum_{I=1}^{N} R_I^{\,2}} \qquad (4\text{-}2)$$

3) Double Sum [18,19,22]

$$R = \sqrt{\sum_{I=1}^{N} \sum_{J=1}^{N} R_I R_J \varepsilon_{IJ}} \qquad \varepsilon_{IJ} = \left[1 + \left(\frac{\omega_I' - \omega_J'}{\beta_I' \omega_I + \beta_J' \omega_J} \right)^2 \right]^{-1}$$

$$\omega_I' = \omega_I \left[1 - \beta_I^2 \right]^{1/2} \tag{4-3}$$

$$\beta_I' = \beta_I + \frac{2}{t_d \omega_I}$$

ω_I = natural frequency for mode I

β_I = damping for mode I

t_d = duration of ground motion

4) Closely Spaced Modes [22]

$$R = \sqrt{\sum_{I=1}^{M} R_I^2 + \sum_{J=1}^{L} \left[\sum_{K=1}^{N_J} R_K \right]^2} \tag{4-4}$$

L = number of groups of closely spaced modes

N_J = number of modes in group J

M = number of separated modes

5) Grouping Method [18]

$$R = \sqrt{\sum_{I=1}^{M} R_I^2 + \sum_{J=1}^{L} \sum_{K=1}^{N_J} \sum_{0=1}^{N_J} |R_{KJ} R_{0J}|} \qquad K \neq 0 \tag{4-5}$$

6) Ten Percent Method [18]

$$R = \sqrt{\sum_{I=1}^{M} R_I^2 + 2\Sigma |R_I R_J|} \qquad I \neq J \tag{4-6}$$

7) Lin's Method [20,21,22]

$$R = \sqrt{\sum_{I=1}^{N} \left[\phi_I(\eta_x + \eta_y + \eta_z)\right]^2} \qquad (4\text{-}7)$$

η_x, η_y, η_z - modal maxima
ϕ_I - eigenvectors

8) Complete Quadratic Combination (CQC) [23]

$$R = \sqrt{\sum_{I=1}^{N} \sum_{J=1}^{N} R_I \, \delta_{IJ} \, R_J} \qquad (4\text{-}8)$$

δ_{IJ} = cross modal coefficients

For analysis of structural systems any one of these equations will give an estimate of the combined maximum peak response of a complex system. The general procedure is to use modal analysis to calculate the peak response for each mode and combine the results using one of the above equations. This combined maximum peak response is then used to calculate an upper bound for stresses in members, which can then be compared to acceptable limits. On the other hand, in the case of the development of a fragility surface for existing qualification data, the interest is to develop a lower bound for the function; therefore it is necessary to modify these procedures. It will be assumed that the qualification testing was performed using swept sine wave excitation at a constant level within the frequency range of interest. During this testing no failure was noted. This data, in conjunction with resonance search results, will be used to develop an acceptable fragility function.

The resonance search data can be used to determine a correction factor to be applied to the swept sine data to account for multimode interaction. The "maximum response", R, is calculated for each axis using the amplified peak response at resonances as the values of R_I, instead of respective peak values from a response spectrum plot. Any one of the equations outlined above can be used. A correction factor α can then be defined as

$$\alpha = \frac{R_{I_{max}}}{R} \tag{4-9}$$

where R_{Imax} is the maximum peak response of any resonances considered. The level of the qualification sine excitation (in the form of a response spectrum, PSD, or RMS amplitude) is then multiplied by this correction factor α, in order to develop an approximate lower bound fragility function, such as the dashed curve in Figure 4.1-1. One caution that must be observed in this approach, is that the resonance data must have been measured at a response point that has a direct relationship to the anticipated failure of the item. That is, the resonance data must have been measured in the vicinity of the location of the critical device which is anticipated to cause failure in the complex system. Should doubt exist, then the conduct of an in-situ resonance search on the system may be necessary.

The following observations are based on the determination of the peak response for structural systems, and will be assumed to hold true for the development of a lower bound fragility function as well. The absolute sum procedure which is the simplest to apply will give the most conservative results, and therefore can be used as a first approximation. If the requirements for qualification are not enveloped by the derived fragility function, one of the other procedures may be used. A number of studies [20,22,23] have shown that the SRSS procedure can be nonconservative for closely spaced modes and therefore should be used with caution. The double sum method takes into account modal interaction through the ε_{IJ} term, which is dependent on the modal frequencies and damping. This is one form that also includes a direct measure of the length of the excitation signal. It has also been shown to be nonconservative in certain instances [22]. The closely spaced modes, grouping method, and ten percent method, all combine the SRSS method for widely spaced modes with an absolute sum or double sum procedure for closely spaced modes. Each of these can be overly conservative [22]. The CQC is similar to the double sum method where the cross modal coefficient is a function of the duration and frequency content of the loading and of the modal frequencies and damping ratios of the structure [23].

When selecting which procedure to use, those that are known to be conservative should be considered first. If the results of these analyses are not acceptable, then the other methods may be used if they can be shown to be conservative for the system under consideration. Each of these procedures can be used to define the level of the approximate fragility function. If these results are still not acceptable, at this point the level of effort required to derive the true fragility surface may be impractical, and requalification of the systems to the new environment may be necessary.

4.3 Statistical Variability of Fragility

The approach outlined above is a deterministic approach in which the actual fragility surface for a complex system has been reduced to a frequency-independent acceptable fragility surface. The various procedures outlined to define the level of the acceptable fragility surface include the assumption that the excitation is timewise random in nature, which has been shown to be true for seismic events [5]. However, in addition to the statistical parameters required to define the seismic event, i.e., frequency content, stationarity, coherence, and probability density, other random variations in the characteristics of the test item and analysis procedures also need to be considered. Livolant [24] looks at the failure probability density function for both analytical and testing procedures used to define structural or functional failures. This requires the definition of both a mean value and a standard deviation associated with the parameter under consideration. Included are:

1) Fragility data developed by analysis:
   a) Uncertainties in the system model including boundary conditions, oversimplified models, and the influence of nonstructural elements.
   b) Uncertainties in damping which can vary with amplitude and frequency.
   c) Uncertainties introduced when combining modal effects.
   d) Uncertainties in the definition of the static and cyclic characteristics of the materials.
   e) Uncertainties as a result of improper definition of the failure mode.

2) Fragility data developed by testing

   a) Uncertainties due to the variations in the fabrication process.

   b) Uncertainties due to low level tests when compared to full-scale excitation.

   c) Variability in the time histories used for testing.

Some additional considerations required during the testing include the data analysis procedures used. The sample length and bandwidth of analysis can introduce additional uncertainties in the result. When considering a probabilistic solution it may be necessary to revert back to a time history solution to account for the influence of the various uncertainties [24]. The added complexities associated with such a probabilistic analysis may not be justified with the present level of information available. The lack of any good definition of the various mean and standard deviations for equipment fragility will limit its applicability. Consideration of uncertainties may also be included in the definition of level of the acceptable fragility curve similar to the +10% required by IEEE 323 in enveloping a TRS with a RRS during testing.

The present intent is to use existing qualification data as an approximation for fragility data in comparing test severities, although in those cases where the result is indeterminate, further acquisition of actual fragility data may be necessary, or complete requalification performed. The following section gives several examples of what is required to use the procedure outline above. In all cases a deterministic approach is discussed. Inclusion of a probabilistic approach is not justified at this time.

5.0 TEST CORRELATION METHODOLODY

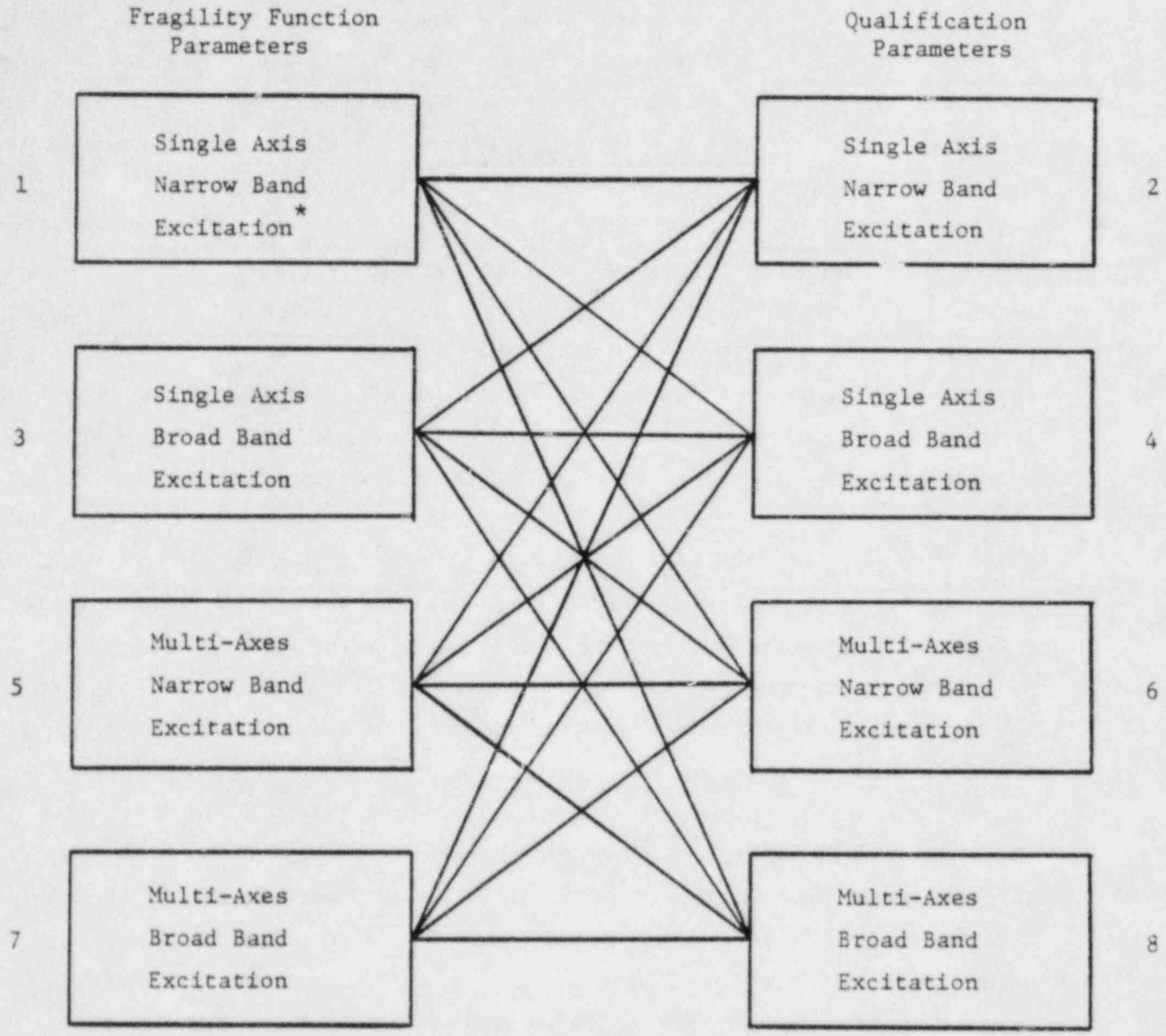
5.1 Fundamental Approach

5.1.1 Qualification, Fragility Estimation, and Test Correlation

At this point it is appropriate to repeat that the primary objective of this work has been to develop a procedure whereby the results that exist from the previous qualification of equipment to one set of criteria may be used to determine whether the same equipment would still be qualified under a different set of criteria. That is, we must correlate the existing data from one qualification test (or analysis) with the requirements of another. The general procedure for this correlation includes the use of a fragility function and damage fragility ratio, D_{FR}. However, the measurement or analytical determination of an exact fragility function (which is useful information for its own sake), may not be necessary for the purpose of the test correlation. Furthermore, exact fragility information on the equipment is very likely not available. Therefore, the procedure further includes the establishment of an approximate, but acceptable, fragility function, which hopefully allows the correlation to be accomplished. The chances of success depend very much on the relative severity of the two sets of criteria being compared, an indication of which can be obtained by the use of the relative damage severity ratio, D_{SR}. Should this approximate procedure provide negative results, acquisition of more accurate fragility information would be necessary to provide a more definite test correlation.

Thus, both qualification and fragility levels are used to establish test severities in the fundamanetal approach to test correlation. The qualification level is that which has been used to qualify the equipment under evaluation. This level may have been measured in terms of a magnitude of a sine wave excitation, a test response spectrum for random excitation, or some other magnitude parameter. Hence, a variety of parameters or their combinations may need to be compared. Figure 5.1-1 shows some possible combinations of parameters that have been used to measure fragility functions and qualify equipment in the past, and may be required at present. The following parameters may be included:

1) Axis of excitation - single or multiple
2) Magnitude - peak or rms amplitude, RRS/TRS, or PSD levels



*Includes sinusoidal excitation

Figure 5.1-1 Possible Combinations of Fragility Function and Qualification Parameters

3) Frequency Content - Narrow band, including sine excitation, or broad band.

For the conditions that are connected by horizontal lines, the procedure for calculating the damage fragility ratio outlined previously can be directly applied. This is the case where the excitation used to derive the fragility function is identical (with respect to axes and frequency content) to the qualification requirement conditions. Those connected with left to right upward sloping lines represent a simplification of the qualification excitation over the fragility function excitation. The procedures given in Section 3.0 can be used to derive the damage fragility ratio for these cases. The final combination (left to right downward sloping lines), whose qualification excitations are more complex than the fragility function excitation, may require extrapolation when interaction is found to be important (see Section 4.0).

5.1.2 Correlation Procedures for Existing Data

The details of applying the above described general procedure to real data that has been acquired or may be acquired on actual equipment depend very much on the specific types of data and equipment under consideration. In this section we will provide several brief examples of how the procedure may be applied. The response spectrum will be used as a parameter for test comparisons, primarily because of its prevalent use in existing data. However use of measured PSD's or transformation between response spectrum and PSD is encouraged freely, if some advantage results from it. Actual examples which include use of other parameters will be given in in Section 5.3.

5.1.2.1 Broadband Response Spectrum

Consider an instrumentation device qualification test that has been applied with an independent biaxial random excitation with a relatively flat energy content between 2 and 50 Hz. The RRS and TRS for one axis of this test are shown in Figure 5.1-2a. This type of data is similar to that presented by Kennedy, et al [10], except that the latter data was obtained for true fragility spectral levels. In the present case, the TRS of Figure 5.1-2a can be considered as an acceptable lower bound fragility response spectrum.

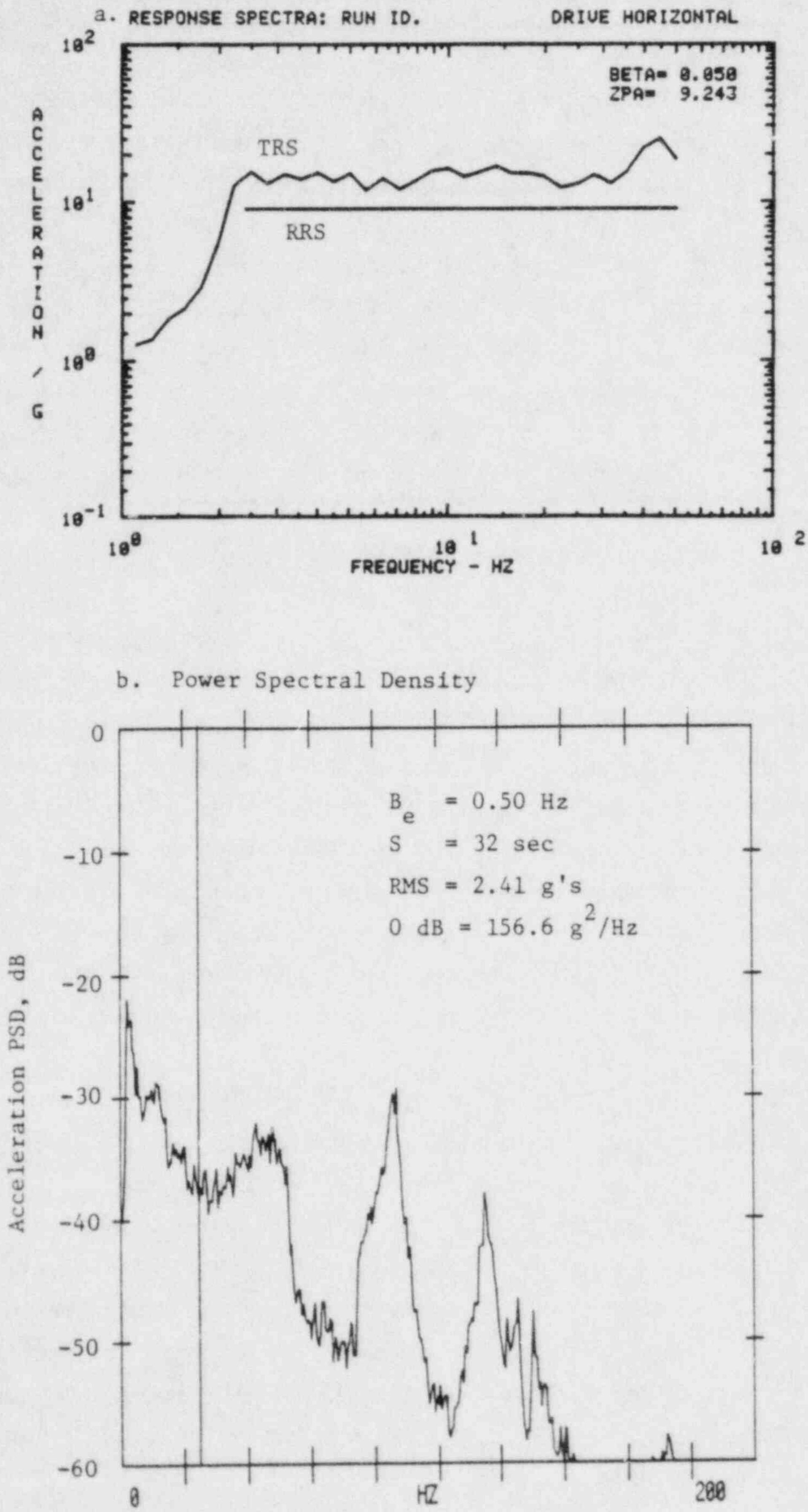


Figure 5.1-2 Broadband Qualification Test

We wish to determine whether the device will be qualified in another environment given by another required response spectrum $R_1(f)$. Of course, in this rather trivial case, we are applying a 7-8 comparison in Figure 5.1-1, and we must determine whether

$$R_1(f) \leq R_{XF}(f) \quad (5-1)$$

where $R_{XF}(f)$ is a fragility response spectrum given by the TRS in Figure 5.1-2a. Even if the indicated TRS did not result from a fragility test, it can be considered a lower bound for the fragility response spectrum. In the latter case, if Equation (5-1) is not satisfied, then a higher level fragility curve must be obtained. Since the excitation was broad band, the data are useful for requalification of the instrument no matter whether it is a simple or complex system.

Shibata [25], Shibata and Okamura [26], and Shibata and Kato [27], have used similar comparisons of required response spectra with fragility response spectra in developing failure margins in structures subject to earthquake loads. However, it is generally accepted that for equipment qualification testing the frequency content of a TRS is often obscured by the presence of unwanted high ZPA's, which are caused by various mechanisms in the test setup. It has been shown in Reference [5] that this problem can be eliminated by the accompanying computation of a PSD. Figure 5.1-2b shows where this has been done for the present example. Thus, transformation of $R_1(f)$ to a PSD, and comaprison with Figure 5.1-2b will allow a better determination of the adequacy of the test signals frequency content.

There is another very important consideration that must be borne in mind with the use of a fragility response spectrum or a fragility PSD that is based on a broad band excitation. Such a fragility function at best states that malfunction or failure of the item in question has been initiated by the input, but the exact frequencies or combination of frequencies that are most responsible for the failure remain undetermined. Thus, the relatively flat TRS in Figure 5.1-2a is a uniform lower bound for the fragility function. If it were so desired, it may be possible that the levels in some relatively insensitive regions of the frequency range could still be increased, since an exact definition of the true fragility function probably has not been achieved. On the other hand, such an exact frequency definition of the true fragility level may be impractical, and therefore a complete requalification may be necessary.

5.1.2.2 Sine Sweep and Simple Equipment

We now consider a case where an instrument device has been subjected to the usual resonance search, with base acceleration constant at 0.2 g. It was then subjected to a uniaxial qualification test, with a 0.5 g sine wave excitation, slowly swept through 2-35 Hz applied along each of three mutually perpendicular axes. No apparent resonances were observed, and the device passed the qualification test with no apparent failures. We now wish to determine whether the device can be considered requalified for a given broad band RRS. The approach involves a 1-8 comparison in Figure 5.1-1.

In view of the results of the resonance search test, the device not only is a simple system, but it is also essentially rigid. A TRS envelope for the qualification test may be drawn at a damping level of 5%, as shown in Figure 5.1-3. This curve may be considered as a lower bound for the acceptable fragility response spectrum, $R_{XF}(f)$. The new RRS, $R_{X1}(f)$ can now be compared, and qualification is preserved providing that

$$R_{X1}(f) < R_{XF}(f) \qquad (5\text{-}2)$$

at all frequencies. It may be noted that this comparison also can be made on the basis of a PSD as well as the response spectrum, if use of that parameter is preferred.

5.1.2.3 Multiple Sine Beats and Simple Equipment

In some earlier qualification tests sine beats at 1/3 octave intervals were typically applied instead of a slowly swept sine excitation. Assume this was the case in the previous example, with peak ZPA levels of 0.5g. A corresponding TRS for the particular sine beat waveform utilized would be generated analytically for each 1/3 octave sine beat. The results would be superimposed and enveloped on a single plot to form a TRS, and in fact an acceptable fragility response spectrum. The new RRS should now be compared directly as in the previous example. It should

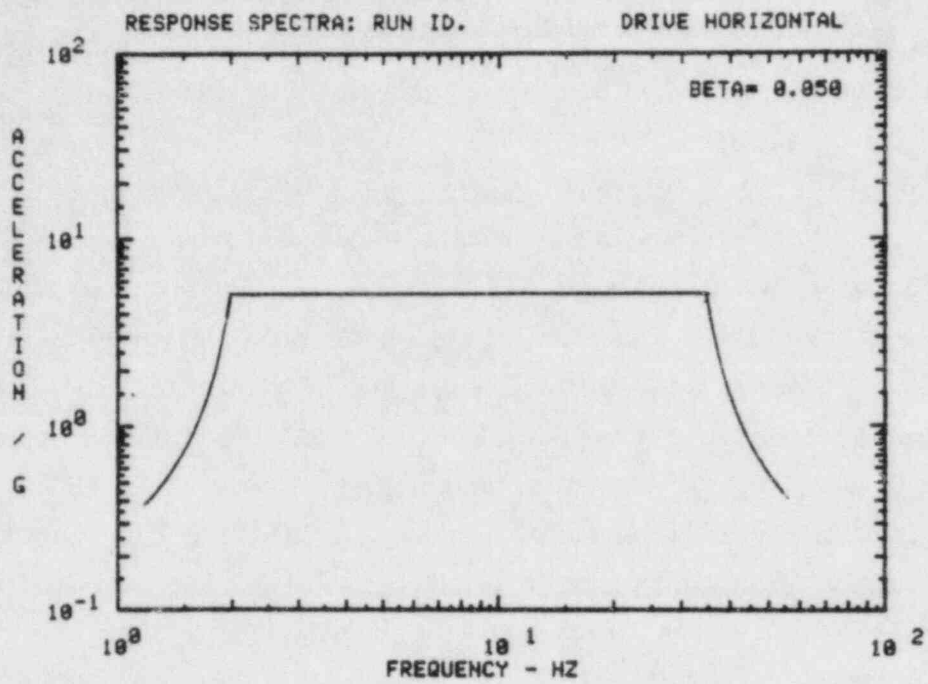


Figure 5.1-3 Envelope for Slowly Swept Sine TRS with 0.5 g ZPA

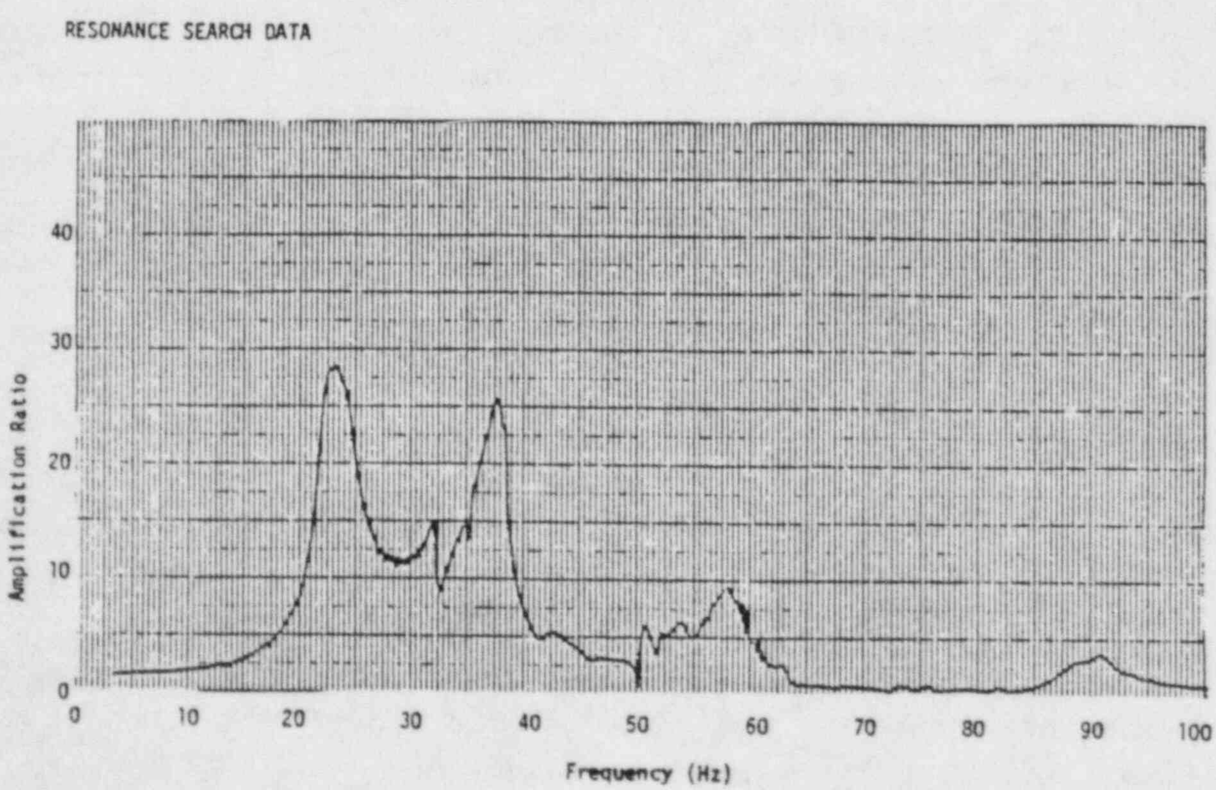


Figure 5.1-4 Instrument Position Transfer Function for Sine Sweep with Fixed Vertical Table for Electrical Rack

be emphasized that both examples involve superposition to obtain the fragility function, and are valid only for simple systems as a result.

5.1.2.4 Sine Sweep and Complex Equipment

Consider a case where the resonance search and qualification test described in 5.1.2.2 has been applied to an electrical rack. The results of the resonance search with an accelerometer mounted at the location of some critical devices is given in Figure 5.1-4. The TRS at 5% damping would again look like Figure 5.1-3. We wish to determine whether the equipment qualifies to a newer given broad band RRS. The approach again involves a 1-8 comparison in Figure 5.1-1; however in this case complex equipment behavior is likely.

A connected lower bound fragility response spectrum based on Figure 5.1-3 must be developed. The best available data for resonances is that from the resonance search. Therefore, it is input to one of the preferred equations of Section 4.1. We select the SRSS approach in Equation (4-2). Note in Figure 5.1-4 that the transfer function is also a direct indication of response sensitivity, and may also be used as input to the correction equations. Therefore, from Figure 5.1-4 we determine that the first resonance response is $R_1 = 28$, and the only other significant resonance has a value of $R_2 = 25$. Therefore

$$R = [28^2 + 25^2]^{1/2} = 37.5 \qquad (5\text{-}3)$$

From Equation (4-9) the correction factor α becomes

$$\alpha = 28/37.5 = 0.75 \qquad (5\text{-}4)$$

Therefore, the acceptable fragility response spectrum is obtained by constructing a corrected curve at 0.75 times the TRS given in Figure 5.1-3. The new broad band RRS can now be compared directly as before.

It is obvious that several variations of this example may be encountered in typical existing qualification data. As a further variation, suppose that no resonance search, per se, had been included. In this case, resonance data may be obtained directly from an in-situ test of the cabinet, by applying excitation at an upper level while the cabinet base is fixed in place. The resulting data will also be satisfactory for input to Equations (5-3) and (5-4). Furthermore, it should always be understood that a PSD may be used as a basis for comparison rather than a response spectrum, if that is preferred.

5.1.2.5 Other Fragility Function Forms

Figure 3.1-1 shows how an acceptable fragility function may have been generated in terms of a PSD function. For currently existing data this would be a rare occurrence, as most existing data will not be in this form. On the other hand, it has previously been emphasized that the exact form of the data generally is of no consequence (except where an excessive ZPA is present), as a transformation from one form to another can be utilized. On the other hand, it is logical to use a parameter that correlates well to the physical failure process in a specimen, if it is known. In any case, it is best to use the simplest possible parameter.

Consider a case where a fragility function of the form in Figure 3.1-1 has been obtained for a specimen. Thus, we have $G_{XF}(f)$ as a function of frequency. It is desired to express this information in terms of a fragility response spectrum. This may be accomplished as follows.

We transform $G_{XF}(f)$ to a response spectrum $R_{XF}(f)$ using the procedures outlined in Reference [6], i.e.,

$$G_{XF}(f) \rightarrow R_{XF}(f)$$

and the objective is accomplished. It must be emphasized that the bandwidth B_e must be the same for both $G_F(f)$ and $R_F(f)$.

In all of the previous examples we have been concerned with whether or not failure did or did not occur. Not much was said about the relative severity of the motions involved in each case. Note that there are two separate questions in the formulation developed. In all of these cases relative severities can be calculated in terms of the damage severity factor D_{SR} by Equations (3-4), (3-5), or (3-21) as appropriate. However, the question of whether failure occurs remains a separate issue to be determined by Equation (3-1) or some similar relationship, depending on the nature of the fragility function. To repeat, the damage severity ratio D_{SR} is used to obtain a relative severity ranking which can indicate the chances of one type of test being more severe than another. However, the actual comparison to the fragility level is given by the damage fragility ratio D_{FR}, which is the basis for vibration equivalence.

5.1.3 Acquisition of More Accurate Data

Conditions may arise in which the available data does not contain sufficient information to approximate either a fragility function or the damage fragility ratio. It then becomes necessary to perform additional tests or analysis to develop the required information for correlation of the tests under concern. Additional testing may also be required if the acceptable fragility function obtained from existing qualification is not sufficiently accurate to allow a positive correlation of the data. Under these conditions, it will generally be more efficient to consider a complete requalification program, rather than attempt to apply the damage fragility ratio correlation procedure. However, for those cases where determination of fragility data is preferred, a discussion of recommended procedures for acquisition of accurate fragility data follows.

The concept of the determination of the actual fragility of a test item has not been uniformly recognized in the nuclear power industry [10], hence procedures outlined here are based on those used in the aircraft industry. In general the procedures used to develop the fragility surfaces are similar, except for the frequency range of interest (less than 33 Hz for earthquake excitation and up to 2000 Hz for the aircraft industry). An important aspect of this difference in frequency range is the use of sinusoidal fragility data for comparison to random environments. For the aircraft industry, "when the environment is random, it is the opinion of the authors that the selection of isolators (or for that matter, the adequacy of the equipment design) cannot be based on sinusoidal fragility data" [28]. On the other hand, for the current problem with excitation up to only 33 Hz, it is felt that the approximate procedures outlined in Section 4.0 can be used to account for interaction between the modes. The unique requirement associated with the nuclear power industry is how currently available qualification data can be used to develop an acceptable fragility surface and then be used to compare to new requirements that may have different excitation parameters.

The first requirement is to define what is to be considered a failure. This is often difficult in practice since only a single component of the total system is to be tested at any one time. In that component a relay may chatter or a needle fluctuate but this may not necessarily constitute a failure. Its influence on the functional characteristics of the entire system is the important consideration. After an acceptable definition of failure is obtained the fragility testing can be performed. Another important consideration in any testing is to insure that the test fixture on which the item is mounted is rigid or that the actual input into the test item is monitored. This is necessary to insure that the fragility levels obtained indicate the sensitivity of the test item and are not influenced by the response of the test fixture.

The actual fragility curve for a simple system can be determined by using either sinusoidal or random excitation. A typical test procedure might begin with uniaxial swept sine or stepped sine testing along three mutually perpendicular axes. For swept sine testing the amplitude of excitation would be kept constant during a sweep through the frequency range. The sweep rate must be slow enough so that each resonance could fully develop. The level would be increased until failure occurs and the frequency at which failure occurred noted. Additional sweeps would be made, excluding the frequency range where failure has been noted, until the maximum excitation level specified is reached. From this data a true fragility function can be defined. For the stepped sine testing the excitation frequency is kept constant and the level slowly increased until failure is noted. The level then can be slowly decreased to determine if there is significant difference between level required to initiate failure and that required to sustain failure. To prevent missing of any susceptible frequencies between the predetermined steps the excitation should be increased to just below the failure level, and slowly swept up or down to the next frequency. In this way an accurate definition of the true fragility function can be obtained. These procedures are repeated for each of the three mutually perpendicular axes to obtain a complete set of fragility fucntions.

It may be only necessary to determine the true fragility function over a limited frequency range if the comparison to the required levels shows deficiencies in certain areas. Care must be taken to insure that these local regions are not influenced by any other modes of the system. For simple systems it is necessary to perform only sine testing to derive an actual and acceptable fragility function. Furthermore, even in complex systems where modal interaction occurs, the procedures outlined in Section 4.2 may be sufficient to allow sine wave fragility testing.

An alternative approach is to use random excitation to derive the fragility function. The important aspect of random excitation is that it can excite multimodes simultaneously, thereby giving an indication of what interaction may occur. Random excitation can be either narrow band or broadband shaped spectrum, each of which has advantages and disadvantages [28]. Narrow band (1 to 2 Hz) excitation will in most cases produce results similar to sine data; therefore it is not necessary to perform both. This procedure will provide a good indication of the frequency dependence of the fragility function but will not provide information on modal interaction. Either swept (shifting center frequency) or stepped random testing can be performed. When performing any random testing, it is important to measure both the RMS and peak levels of the excitation. A PSD of each level should also be calculated and recorded. The bandwidth of the excitation can be increased until it matches the maximum expected for the in-service condition. The broadband excitation can be either flat or shaped. For a flat spectrum the spectral density is constant throughout the frequency range. The level of the spectrum is increased until the first sign of failure occurs.

It may be noted that the above sequence progresses from simple tests to more complex tests. This approach obviously is appropriate if a simple system result is anticipated. However, if a complex system result is anticipated at the outset, then starting with the more complex tests immediately would be appropriate. The flat random excitation may be considered to be the most efficient waveform for acquisition of new fragility data.

To obtain additional information on the shape of the fragility curve the spectral densities in discrete frequency bands may be reduced to determine the effect on the failure [28]. The level is reduced in successive bands until failure no longer occurs. The PSD in this region should then be kept constant, at a level where no failure occurs, and the remainder of the frequency range increased until failure is again noted. This procedure is repeated until an adequate definition of the shape of the curve is obtained or the maximum required excitation level is obtained. This procedure should provide significant information on any modal interaction that may occur. If the PSD levels in the notched regions have to be reduced during the testing, it could be the result of either modal interaction or the absolute level of excitation. The last random procedure is the shaped spectrum. In this case the PSD profile has the same shape as the service environment and will produce a fragility function which is proportional to the service environment of all frequencies [28]. The level of the shaped function is slowly increased until the first indication of failure is obtained. This procedure is good for specific requirements but does not have as broad of an application to subsequent requalification.

The majority of fragility testing has been performed using uniaxial excitation. It may be necessary to perform some multiaxes excitation if interaction is determined to be significant. Test parameters for multiaxes test can become extremely complicated and should reflect requirements for the specific item under consideration. An alternative approach to multiaxes testing is to use the procedures defined in Section 4.2 to define an acceptable fragility function.

No matter how any more accurate fragility data has been acquired, subsequent use of this data for test correlation is performed according to the general procedures outlined in previous sections.

5.2 Verification of Fragility Concept

5.2.1 Equipment Devices and Assemblies

Up to this point discussion of the fragility function has been general, in that it has dealt with an arbitrary specimen and used for test comparisons for such a specimen. It is now necessary to look at the determination of fragility functions and fragility ratios of typical equipment devices and assemblies, as they are considered for equipment qualification purposes. Furthermore it is appropriate to study some data acquired from typical hardware specimens to verify that application of the fragility concept indeed is practical.

A device is the smallest entity for which the input can be uniquely defined and the function characteristics measured. Typically, it may be a relay, a valve, an instrument, a cabinet, etc. Relays, valves, and instruments can easily be visualized as a device. For cabinets the concern is definition of the excitation and interaction associated with local panel modes and rattling of doors, which make it difficult to separate out the individual components. An assembly is a collection of devices. The required input motion is defined for the support points of the assembly and the resulting excitation levels can be measured at the device location. Functional characteristics can be defined for the individual devices or the assembly with devices installed. The assembly is important because many qualification programs have been performed on assemblies, and the comparison to new requirements will necessarily be on the assembly level. The concept of a device is important because qualification is also performed on devices and it may be difficult to develop an acceptable fragility surface on an assembly level.

5.2.2 Application to Specific Devices

A number of tests were performed to attempt to verify the procedures outlined above, when applied to actual equipment specimens. Two particular devices were studied in some detail, a Yarway Level Indicator/Switch and a Barksdale Pressure Switch, both of which were included in previous studies [5] of an electrical rack. For the present study, both devices were mounted on one-eighth-inch support plates which were then attached to a UNISTRUT member (the in-service condition). The UNISTRUT was then rigidly attached to a "rigid" bookend and mounted on the seismic simulator. This mounting was used to facilitate later comparison to assembly test results that had been acquired earlier [5]. The test procedures to follow can be considered good examples of accurate determination of fragility functions.

The Yarway was subjected to stepped sine, narrowband random, and broadband random testing. The broadband testing was part of a qualification program, while the stepped sine and narrowband random results were obtained during subsequent fragility tests of the instruments. These latter results will be discussed here, in order to derive acceptable fragility functions. The results of the stepped sine and narrowband random test for X-axis (front to rear) excitation is summarized in Table 5-1. Failure was defined as the occurrence of chatter in the instruments relay circuits. These data were obtained by direct measurement of peak and true RMS values from the excitation as chatter was initially observed . All results indicate a dip in the fragility curve at 22 Hz for the sine testing, 22 Hz for the 2 Hz bandwidth testing, and 20 Hz for the 5 Hz bandwidth testing. Another dip occurs at 27 and 28 for the sine and 2 Hz results, but is not evident for the 5 Hz testing. This would tend to indicate a sharp dip which did not have sufficient excitation in the 5 Hz testing to allow buildup. Another interesting point is the variation in peak/RMS ratio for the random testing. Near the resonance at 22 Hz the value decreases which indicates some interaction between the test item and the drive system. From this tabular set of data it is possible to develop an acceptable fragility function. A stepped sine test at 0.6 g's peak acceleration from 5 to 35 Hz, a 2 Hz bandwidth random excitation at 1.0 g's peak from 2 to 32 Hz, or a 5 Hz bandwidth random excitation at 4.0 g's peak from 5 to 35 Hz could all be considered an acceptable fragility function.

Figures 5.2-1 to 5.2-3 are graphical representations of further reduction of the data from Table 5-1. Figures 5.2-1 and 5.2-2 show the RMS and peak accelerations respectively as a function of frequency. An important consideration when interpreting this information is the statistical variations possible. With the Yarway adjusted to an indicated 60 inches of water, fourteen different fragility level sample values were obtained for sinusoidal excitation at 10 Hz, since some statistical scatter of data was observed. The mean, 3.41 g's peak, and standard deviation, 0.93 g's peak, values were calculated. Additional measurements at zero psi differential pressure (>60" of water) gave a mean of 2.4 g's peak and a standard deviation of 0.75 g's peak. These variations are significant and should be considered in all types of testing. The standard deviation will most likely be different for all types of instruments. In addition to variations in the level required to induce failure, one must also consider the level of confidence associated with the measure and/or calculated peak and RMS values.

It was anticipated that a PSD function should be a very useful form of presenting the fragility data. One possible method of doing this is to square the RMS value and divide by the appropriate bandwidth of

TABLE 5.1 YARWAY FRAGILITY TESTING RESULTS, X-AXIS

Sine Data*		Narrow Band Excitation Data							
		2 Hz Bandwidth				5 Hz Bandwidth			
Frequency (Hz)	Peak Acceleration g's	Center Frequency (Hz)	Peak Acceleration g's	RMS Acceleration g's	Peak to RMS Ratio	Center Frequency (Hz)	Peak Acceleration g's	RMS Acceleration g's	Peak to RMS Ratio
		2	1.1	0.20	5.50				
		4	2.2	0.47	4.68				
5	3.4					5**	4.0	0.71	5.62
6	2.9	6	3.9	0.64	6.09				
7	2.4								
8	4.7	8	4.2	0.74	5.68				
9	4.8								
10	3.8	10	5.1	1.02	5.00	10	9.5	1.55	6.13
11	4.4								
12	3.4	12	4.9	1.30	3.77				
13	3.6								
14	4.4	14	8.7	1.50	5.80				
15	4.2					15	12.2	1.67	7.32
16	2.6	16	5.0	1.50	3.33				
17	2.9								
18	3.6	18	4.5	1.23	3.66				
19	2.4								
20	2.8	20	3.8	1.19	3.19	20	4.4	1.36	3.23
21	1.9								
22	1.7	22	2.3	0.82	2.81				
23	2.3								
24	3.0	24	6.4	1.73	3.70				
25	4.2					25	7.2	1.9[illegible]	3.79
26	0.8	26	4.4	1.23	3.58				
27	0.7								
28	0.9	28	4.6	1.15	4.00				
29	2.4								
30	1.1	30	5.5	1.36	4.04	30	6.2	1.48	4.20
31	1.8								
32	1.6	32	5.2	1.16	4.48				
33	1.3								
34	2.2	34	3.0	1.13	3.36				
35	0.6					35	4.5	0.72	4.91

*Peak to RMS ratio assumed to be equal to 1.41.
**No Failure Maximum Table Input.

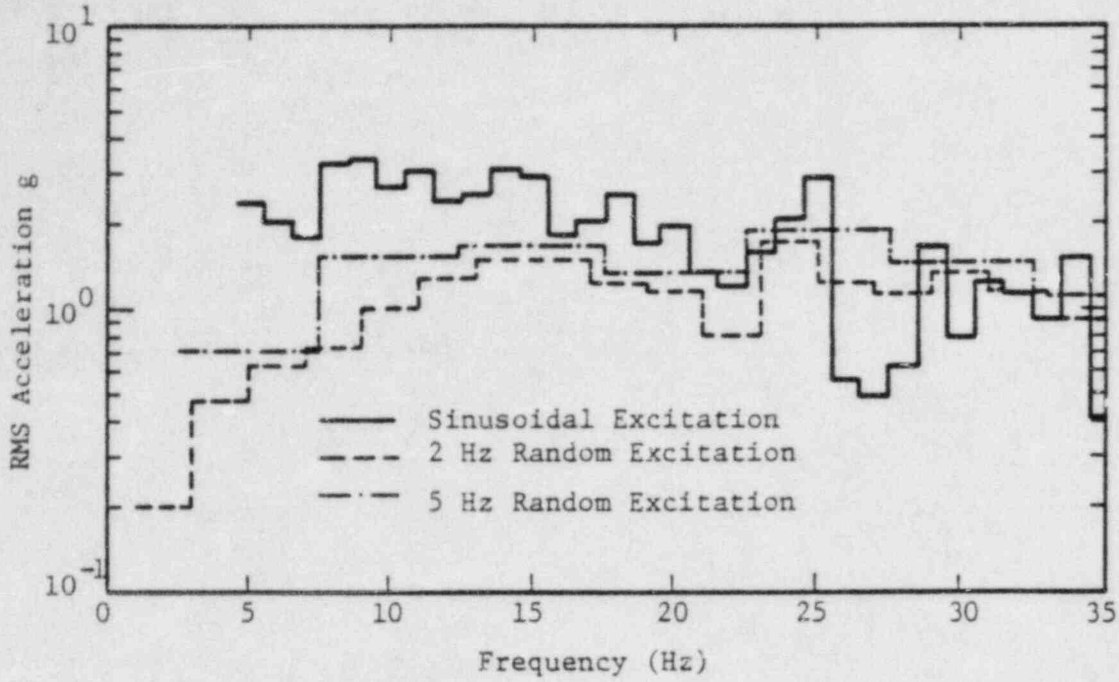


Figure 5.2-1 RMS Acceleration Fragility Function for Yarway, X-Axis

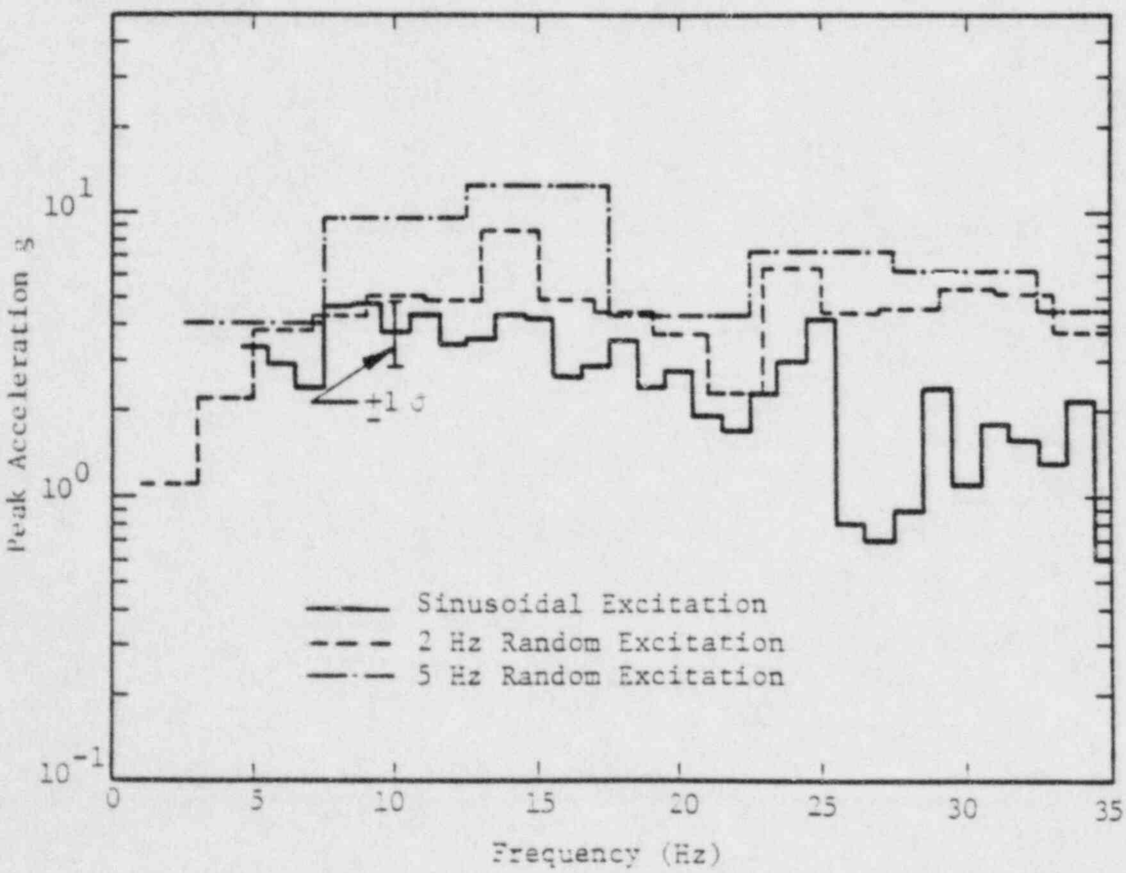


Figure 5.2-2 Peak Acceleration Fragility Function for Yarway, X-Axis

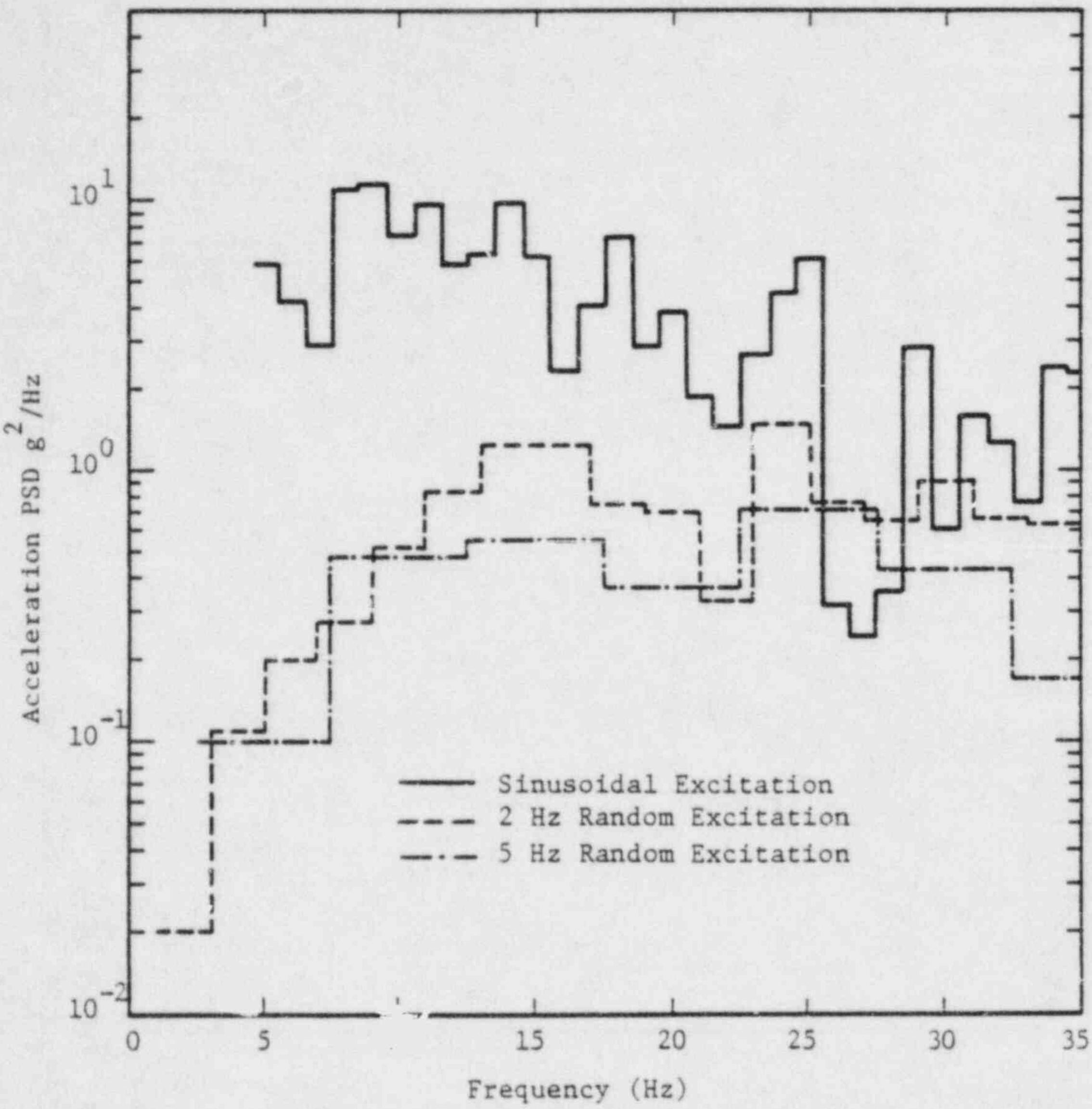


Figure 5.2-3 Calculated PSD Fragility Function of Yarway, X-Axis

excitation; 1 Hz for sinusoidal, 2 Hz for 2 Hz bandwidth excitation, and 5 Hz for 5 Hz bandwidth excitation (Figure 5.2-3). The wide dispersion between the sine data and the random data below 25 Hz indicates that the peak acceleration may be more significant than the RMS levels in this region.

An alternative approach to the development of a PSD fragility function for the Yarway instrument is given in Figures 5.2-4 to 5.2-6. Figure 5.2-4 is a replot of the sine results given in Figure 5.2-3, so that it can be compared on the same scale to the measured PSD's given in Figures 5.2-5 and 5.2-6. The latter PSD's were calculated directly from the same fragility excitations directly by using a Nicolet 444A spectrum analyzer with eight samples of data and an analysis bandwidth of 0.25 Hz. These results are consistent with those shown in Figure 5.2-3, which indicates that either method of detailed measurement is acceptable. Similar results were obtained for Y-axis (side-to-side) and Z-axis (vertical) excitation of the Yarway.

The test results described previously were measured from a series of acurate fragility tests, rather than approximated from qualification tests. If an X-axis stepped or swept sine wave test from 5 to 35 Hz had been performed at a PSD level of 0.2 g^2/Hz, no failures would have occurred and an acceptable fragility function would have been established. This acceptable fragility function would be extremely conservative below 25 Hz (although this fact is only known because of the acquisition of the accurate data). The sensitivity of the test item to low frequency random excitation make the development of a flat fragility function difficult. For 2 Hz excitation this would require a level of 0.02 g^2/Hz from 2 to 34 Hz. The corresponding 5 Hz excitation level would be 0.1 g^2/Hz from 5 to 35 Hz. Thus, it appears that for the 2 Hz excitation it would be more reasonable to provide an approximate fragility function that increases linearly from 0.02 g^2/Hz at 2 Hz to 0.3 g^2/Hz at 10 Hz, and is constant at that level out to 34 Hz.

A second series of tests were performed with the Yarway subjected to broadband random excitation. The PSD's and shock response spectrum for a simulated earthquake event for which no failure was noted are given in Figures 5.2-7 and 5.2-8. Although the functional parameters for the run were slightly different than the current requirements, they can

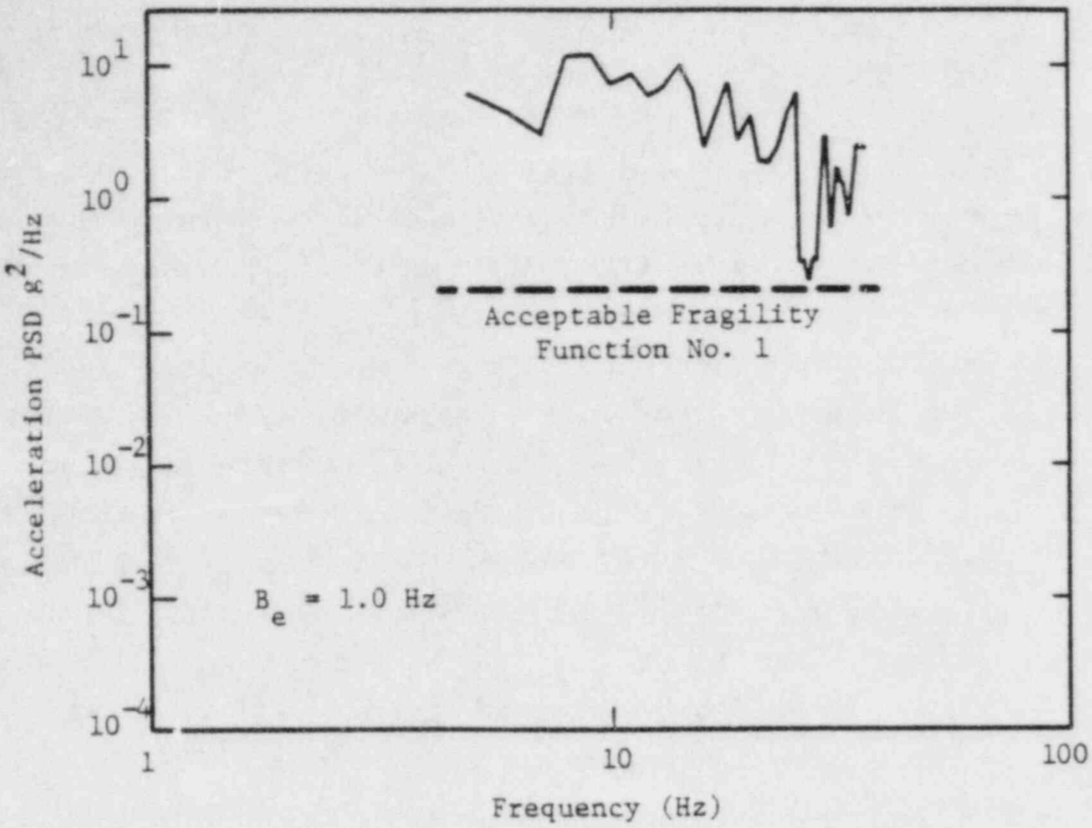


Figure 5.2-4 Sinusoidal Excitation PSD Fragility Function for Yarway, X-Axis

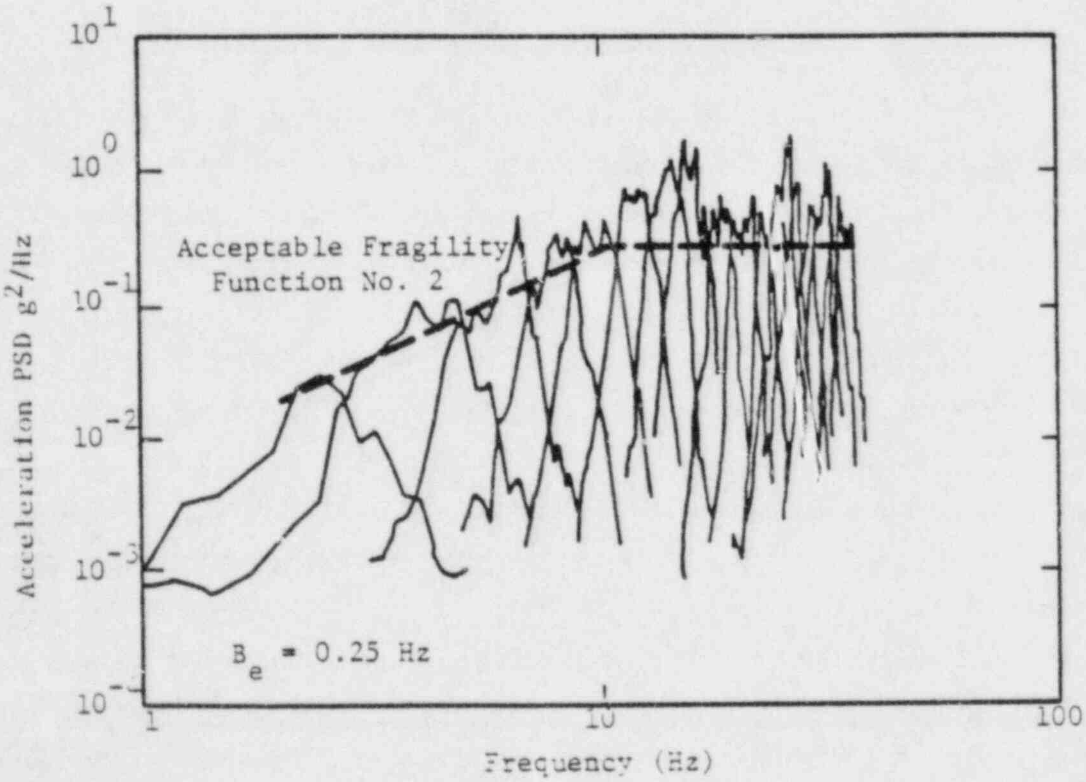


Figure 5.2-5 2 Hz Bandwidth Random Excitation PSD Fragility Function for Yarway, X-Axis

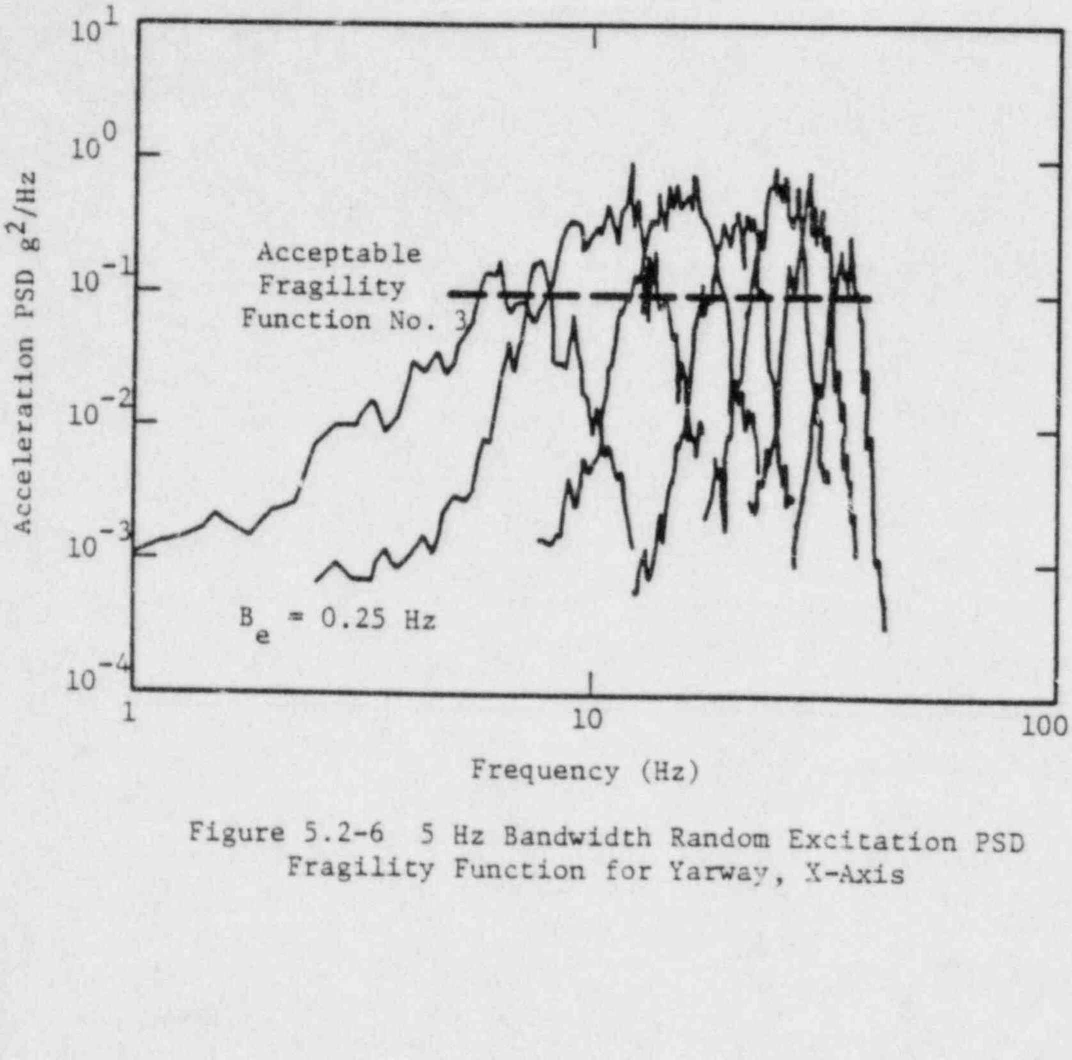
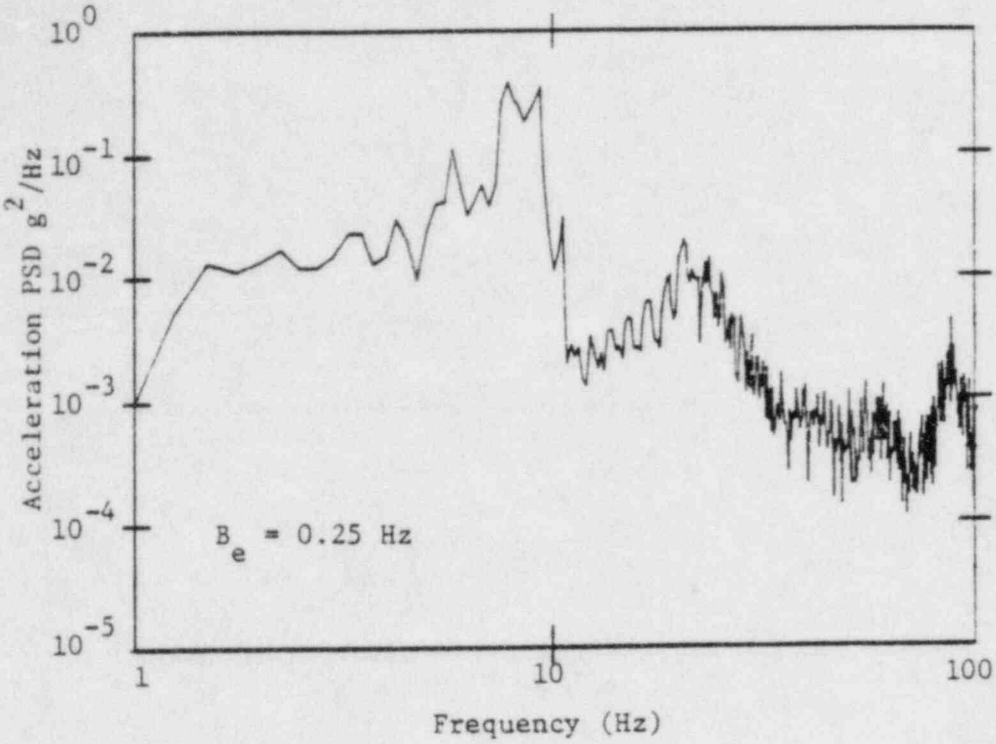


Figure 5.2-6 5 Hz Bandwidth Random Excitation PSD Fragility Function for Yarway, X-Axis

a. Horizontal



b. Vertical

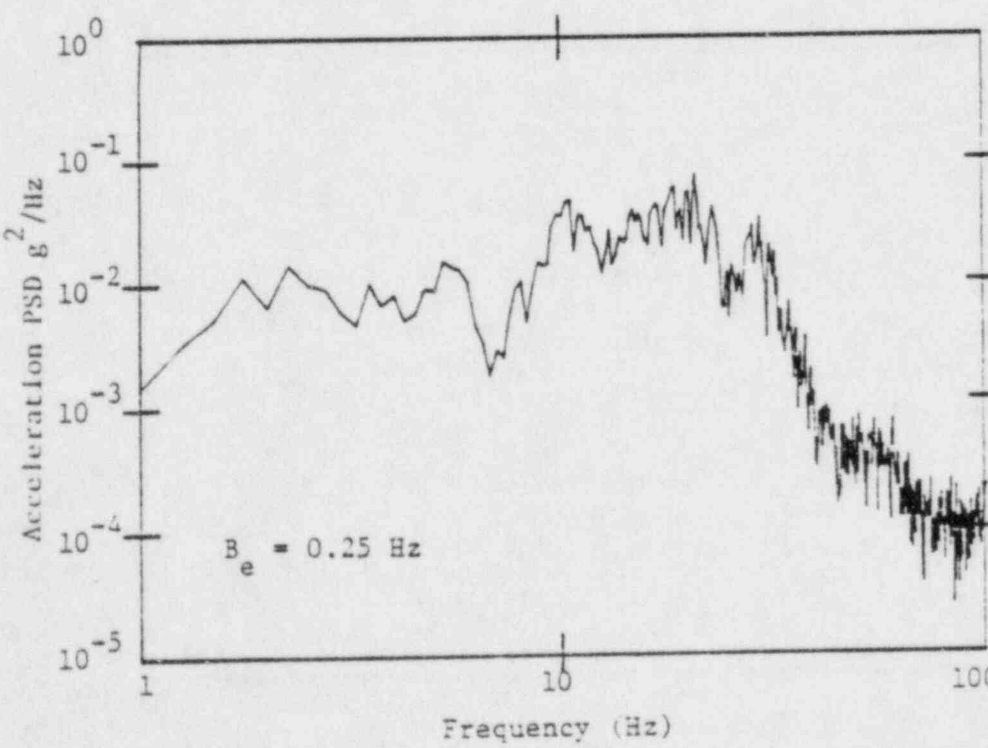


Figure 5.2-7 Broadband PSD Fragility Function for Yarway

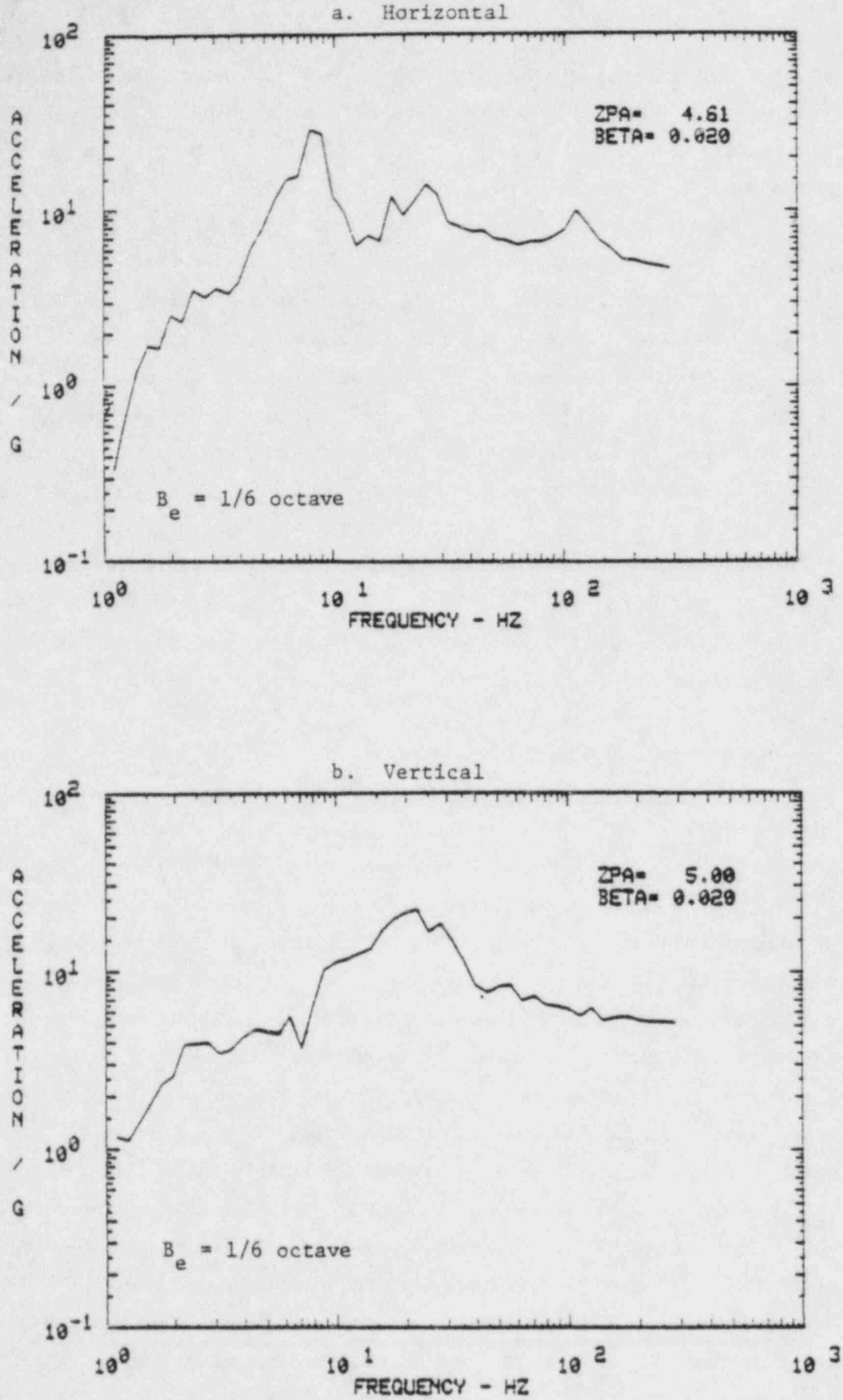


Figure 5.2-8 Broadband TRS Fragility Function for Yarway

still be used for comparison. Either the PSD, which gives a better indication of energy, or the shock response spectrum can be used directly as an acceptable fragility function. Note that only the broadband results are for biaxial excitation. All other results are based on uniaxial excitation. For this case it was assumed that no interaction between axes was present.

A less extensive test series was performed on the Barksdale Pressure Switch. This device required extremely high levels of input to induce a failure, which was defined as a complete change of state of the lower set point switch. Only stepped sine wave excitation was applied to the test item. For X-axis excitation no failure was introduced for peak acceleration which varied from 10 g's at 5 Hz to 6 g's at 35 Hz. These peak levels were set as a result of table limitation. Similar results were obtained for the Y and Z axes of excitation. For all three axes of excitation an acceptable fragility level of 6.0 g's peak sinusoidal excitation can be defined. This corresponds to a PSD level of 36.0 g^2/Hz from 5 to 35 Hz for sinusoidal input.

5.2.3 Assembly Considerations

The test items described above were also mounted on an electrical rack for assembly testing. In this way, procedures applicable to assemblies could be verified. In assembly testing the qualification of the assembly as a whole or each separate device mounted on the assembly can be accomplished. For the assembly a definition of the excitation levels and measurements of the functional characteristics are required. For device qualification it is also necessary to obtain information on the excitation levels at the device locations on the rack. The excitation levels at these locations can be measured directly during the testing or derived from the input levels if an as-tested transfer function is known. In this case the assumption of a linear elastic system is usually made.

Figures 5.2-9 and 5.2-10 give the directly computed PSD's and TRS's for base input motion into the rack. These can be used directly as acceptable fragility functions if requalification is to be done on an assembly level. If significant resonances of the assembly are present, it is important to consider the relative frequency distribution of the excitation motion. If there is significant variation in the old and new

a. Horizontal

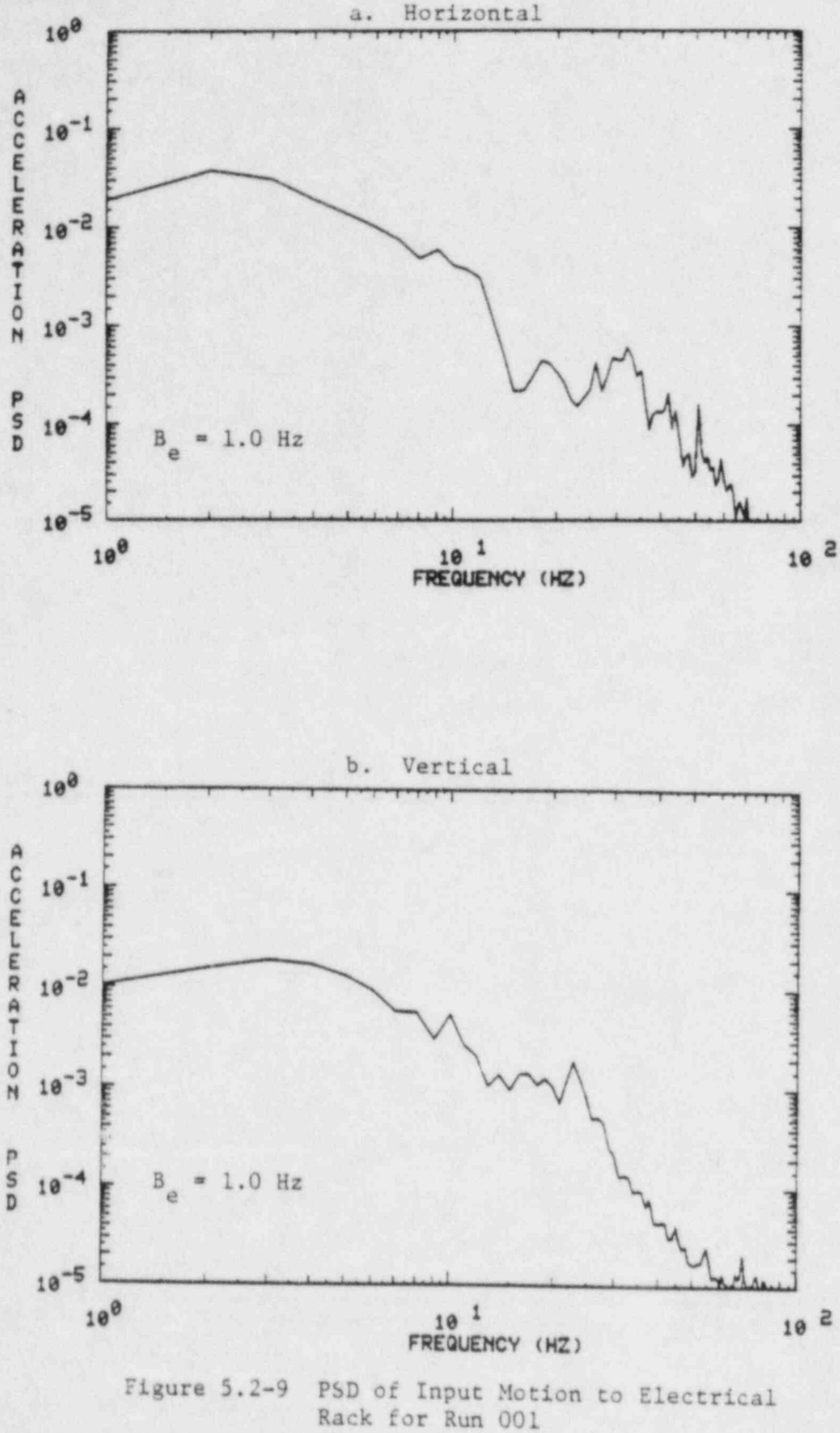
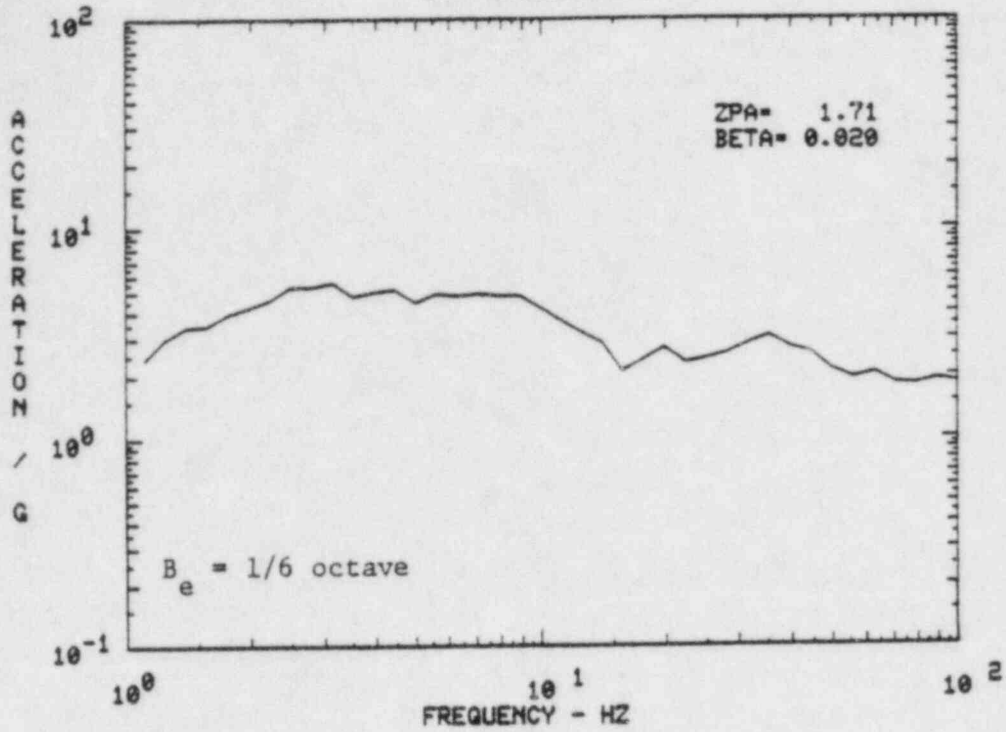


Figure 5.2-9 PSD of Input Motion to Electrical Rack for Run 001

a. Horizontal



b. Vertical

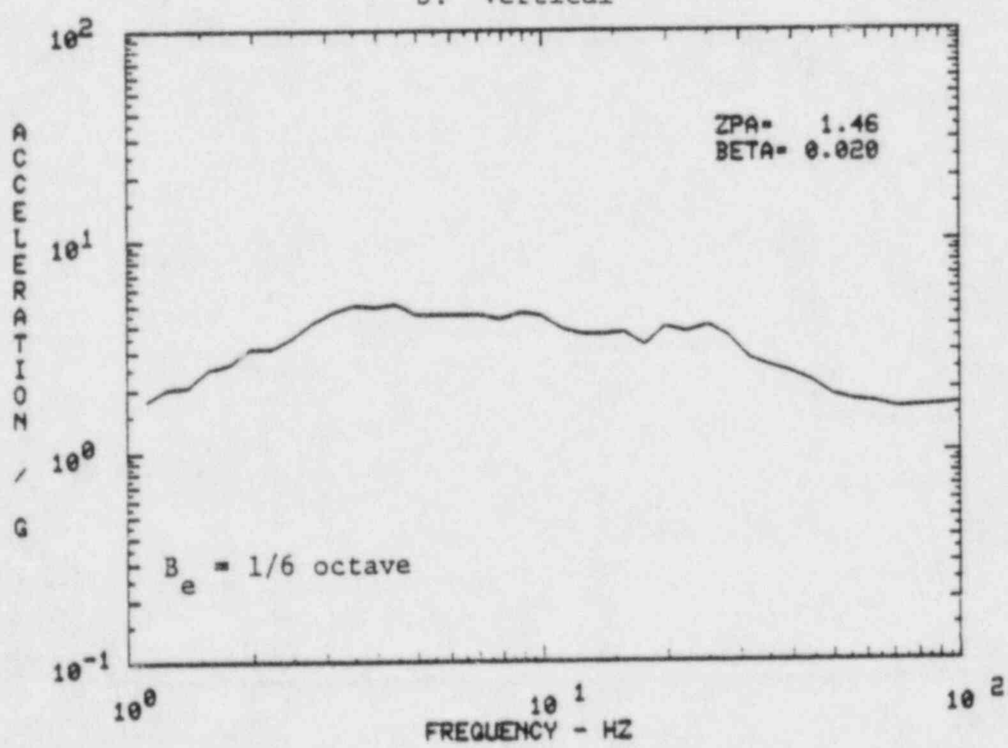


Figure 5.2-10 TRS of Input Motion to Electrical Rack for Run 001

requirements, which will result in changes in the elevated response spectrum at the device locations, it may be necessary to define the acceptable fragility function for a device at the device level.

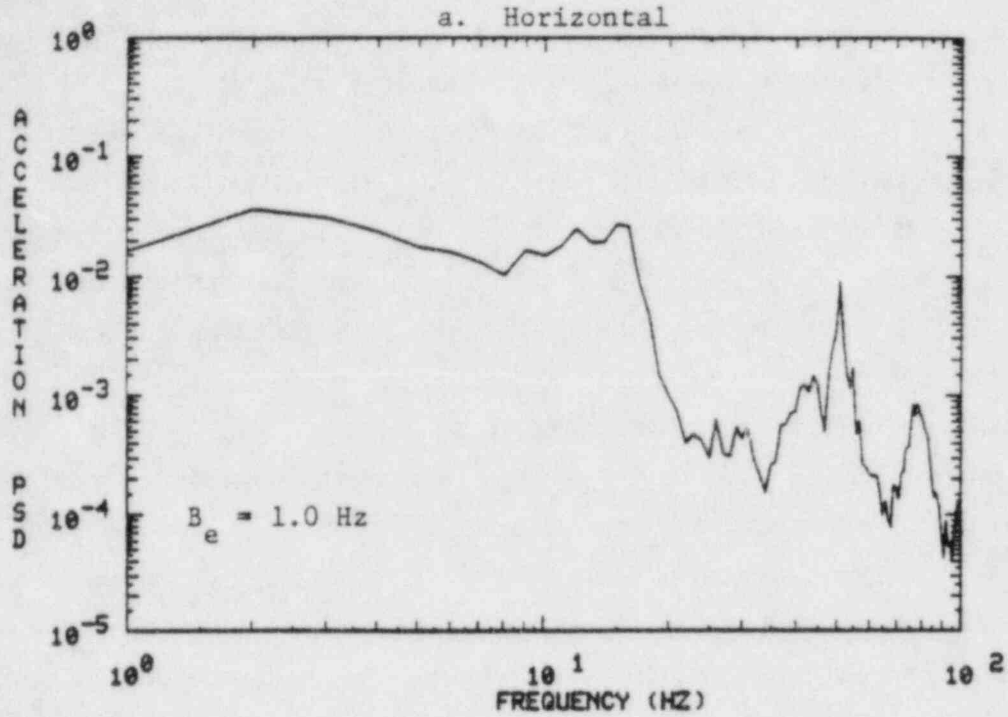
There are two methods that can be used to develop device specific acceptable fragility functions. The first is to use the measured accelerations at that level and calculate the PSD and/or TRS at that location (Figures 5.2-11 and 5.2-12). These can be defined as the acceptable fragility function for this specific device mounted at the given location on the electrical rack. The alternative procedure is to use the as-tested transfer function and transform the base PSD's and/or TRS's to the device location, Figure 5.2-13. One important consideration is the definition of the transfer function. In Reference [5] it was demonstrated that there could occur significant variations in the transfer function measured for a "rigid" base and the as-tested moving base conditions, due to test item and table interaction. Figure 5.2-13 shows the differences noticed for X-axis response of the Yarway location during testing of the electrical rack.

5.3 Examples For Correlation of Qualification Tests

5.3.1 Yarway Device

Section 5.2 dealt primarily with the development of an acceptable fragility function using a number of different procedures. It now becomes appropriate to apply this function to correlation with the requirements of other possible qualification test specifications. To review, several examples of acceptable fragility functions for X-axis excitation of the Yarway device are given in:

Fragility Function No.		
1	Figure 5.2-4	PSD level for sine excitation which can be approximated by a constant level at 0.2 g^2/Hz (5 to 35 Hz)
2	Figure 5.2-5	PSD level for 2 Hz random excitation which can be approximated by a linear function (on log-log paper) from 0.02 g^2/Hz at 2 Hz to 0.3 g^2/Hz at 10 Hz, and 0.3 g^2/Hz from 10 to 34 Hz (2 to 34 Hz)



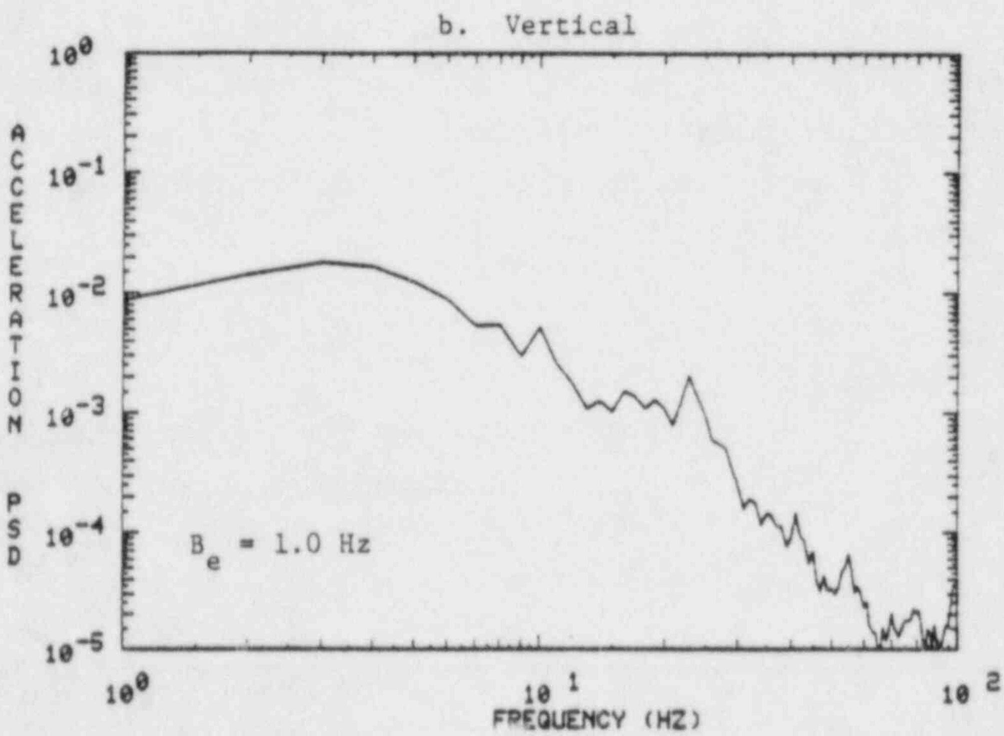
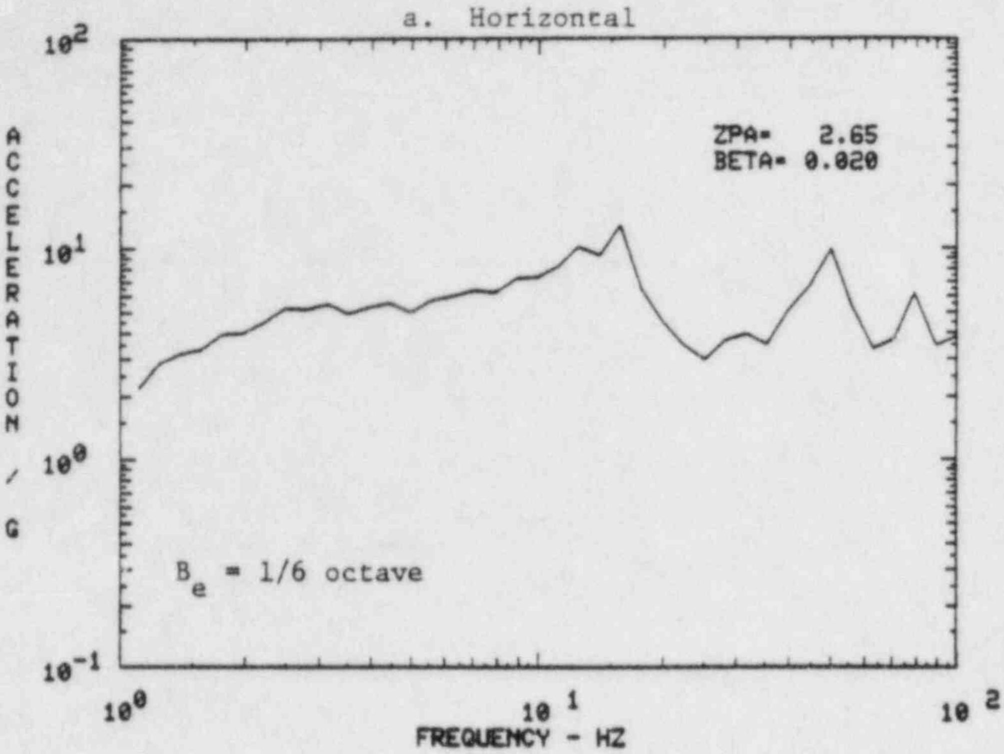


Figure 5.2-11 PSD at Yarway Location on Electrical Rack for Run 001



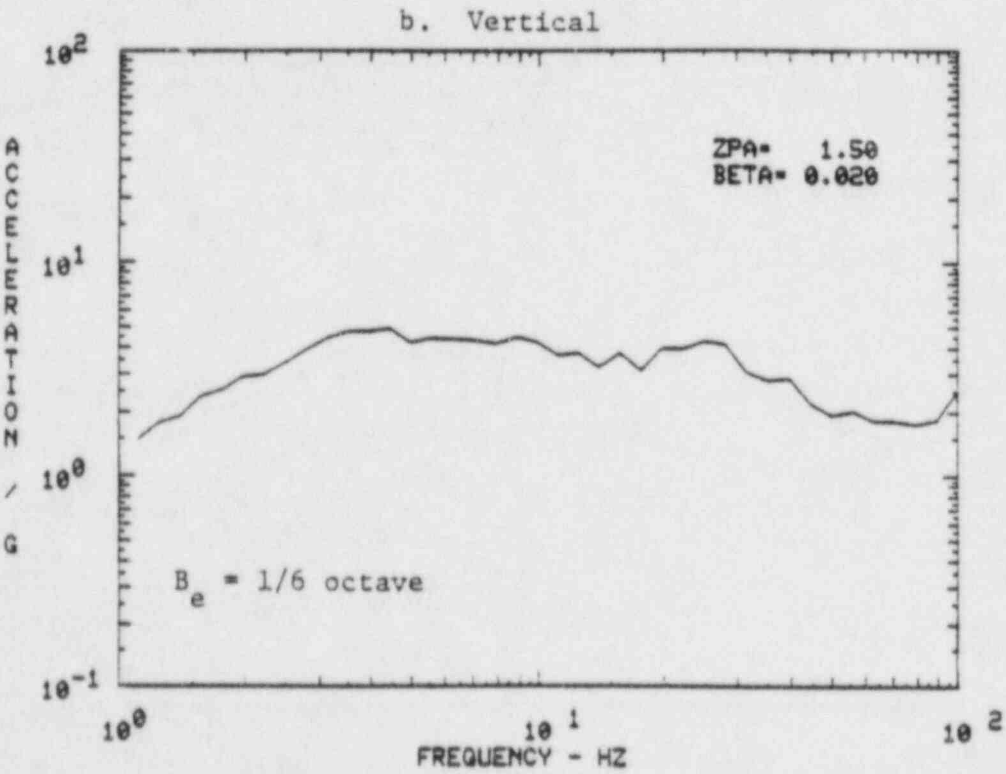


Figure 5.2-12 TRS at Yarway Location on Electrical Rack for Run 001

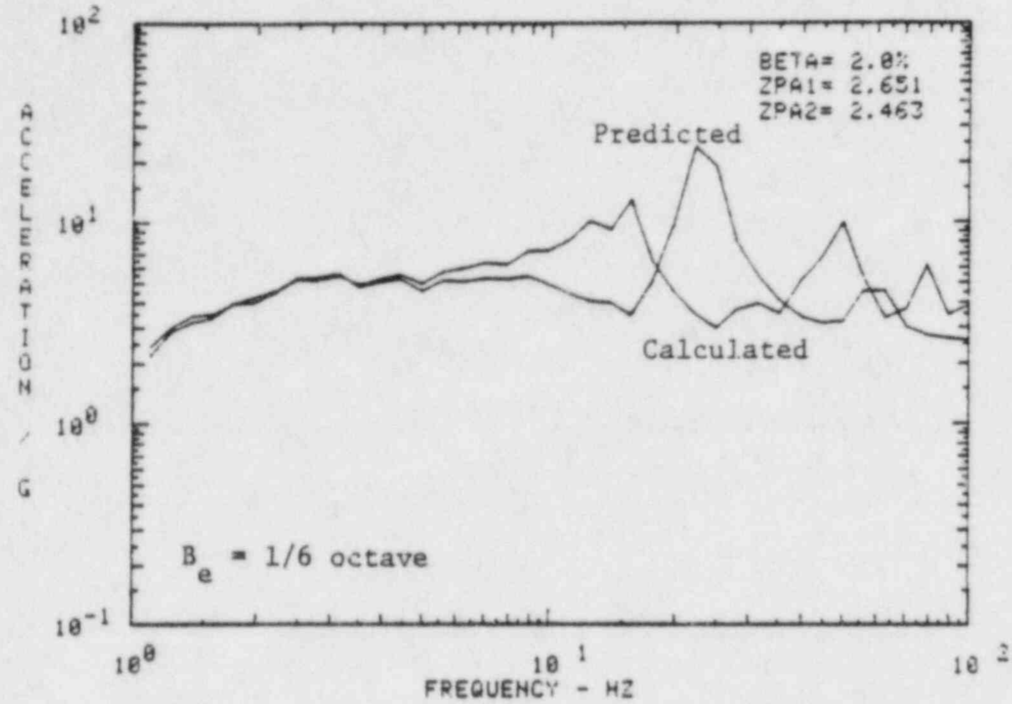


Figure 5.2-13 Calculated and Predicted TRS Levels for Yarway Location on the Electrical Rack

3	Figure 5.2-6	PSD level for 5 Hz random excitation which can be approximated by a constant level at 0.1 g^2/Hz (5 to 35 Hz)
4 (PSD) 5 (TRS)	Figures 5.2-7 and 5.2-8	PSD and TRS levels for random input to be used directly (1 to 1000 Hz)

Requalification to a specified sinusoidal excitation will be considered first. Assume that the new qualification requirement specifies swept sine testing at both 0.3 g's peak and 1.0 g's peak, from 2 to 33 Hz. The 0.3 g's level would correspond to a constant PSD level of 0.09 g^2/Hz. Acceptable fragility function No. 1 could be used for qualification only if ignoring frequencies below 5 Hz can be justified. Functions Nos. 2 and 4 indicate that failure is possible below 5 Hz, and ignoring such frequencies cannot be justified. Function No. 3 suffers the same restriction as No. 1, in that no data is actually available below 5 Hz. It is important to remember that these procedures indicate only the possibility of failure, and additional tests can be performed to determine the actual fragility levels or new qualification levels. For tests performed on the Yarway it has been shown that the item does not fail due to a 0.3 g's sinusoidal input in the X-axis. The probable reason that functions 2 and 4 indicate possible failure is that the device is more sensitive to peak acceleration at the low frequencies rather than the RMS level, as plotted on the PSD. The random signals had peak/RMS values ranging from 3.2 to 7.3 in comparison to the sine excitation at 1.414. Because of this, the RMS based random fragility function will be overly conservative in the low frequency range. If the required acceleration level was increased to 1.0 g's peak (1.0 g^2/Hz), all fragility functions would indicate the possibility of failure, which did in fact occur during testing.

Narrow band testing will be considered next, although qualification will normally not be specified in terms of narrow band tests. If a narrow band (2 to 5 Hz) excitation level of 0.1 g^2/Hz is specified from 2 to 33 Hz only, Fragility Function No. 1 based on sine data could be used. In fact, it would erroneously show that no failures would occur, which is in error considering the results of Figure 5.2-3. It is important to consider both peak and RMS values in defining the fragility function. For the Yarway it is sensitive to peak acceleration in the low frequency range.

This demonstrates the difficulty involved in going from a simple excitation fragility function to a complex required excitation. In this case the procedures outlined in Section 4.1 would not be applicable because an accurate definition of the actual fragility surface would not be available. If the required level was reduced to 0.01 g^2/Hz, acceptable Fragility Function No. 2 could be used. Function No. 3 again does not include the lower frequencies, and function No. 4 is below the required level above 10 Hz. This would indicate failure was possible, and additional tests are required if qualification to this level is desired.

Requalification to a broadband random excitation will be the last example shown for a device level test. First consider the PSD and TRS levels given in Figures 5.2-7 and 5.2-8 as the required qualification levels. In this case failure will be assumed to be a function of X-axis excitation only. Using the simplified acceptable fragility functions 1 to 3, all would indicate possible failure, due to the peak in the required PSD from 6 to 9 Hz. Therefore additional data would be required for requalification. However, if from Figures 5.2-4 to 5.2-6 we use the actual measured fragility functions (rather than the simplified acceptable levels), then requalification is successful. That is, Figure 5.2-4 (the sine-produced failure function) indicates no failure, although the peak/RMS problem discussed above must be considered. Further, using the 2 Hz data the results are acceptable, although the curves are extremely close between 5 and 10 Hz. In this case one must consider the statistics associated with the measured fragility function and the actual qualification requirements. If the factors of safety applied to the qualification levels are known, it is possible to assume a valid qualification although care must be taken.

Consider the PSD given in Figure 5.3-1 as another example of a required requalification. The procedure defined above can be repeated. In this case only the random curves (Figures 5.2-5 and 5.2-6) will be used. Both the 2 Hz and 5 Hz acceptable and actual fragility functions show the possibility of failure due to the peak in the required PSD between 1.5 and 3.0 Hz. As noted earlier, this is the region where peak acceleration is important and the sine data would give possible erroneous results. It is known that failure did occur for the test.

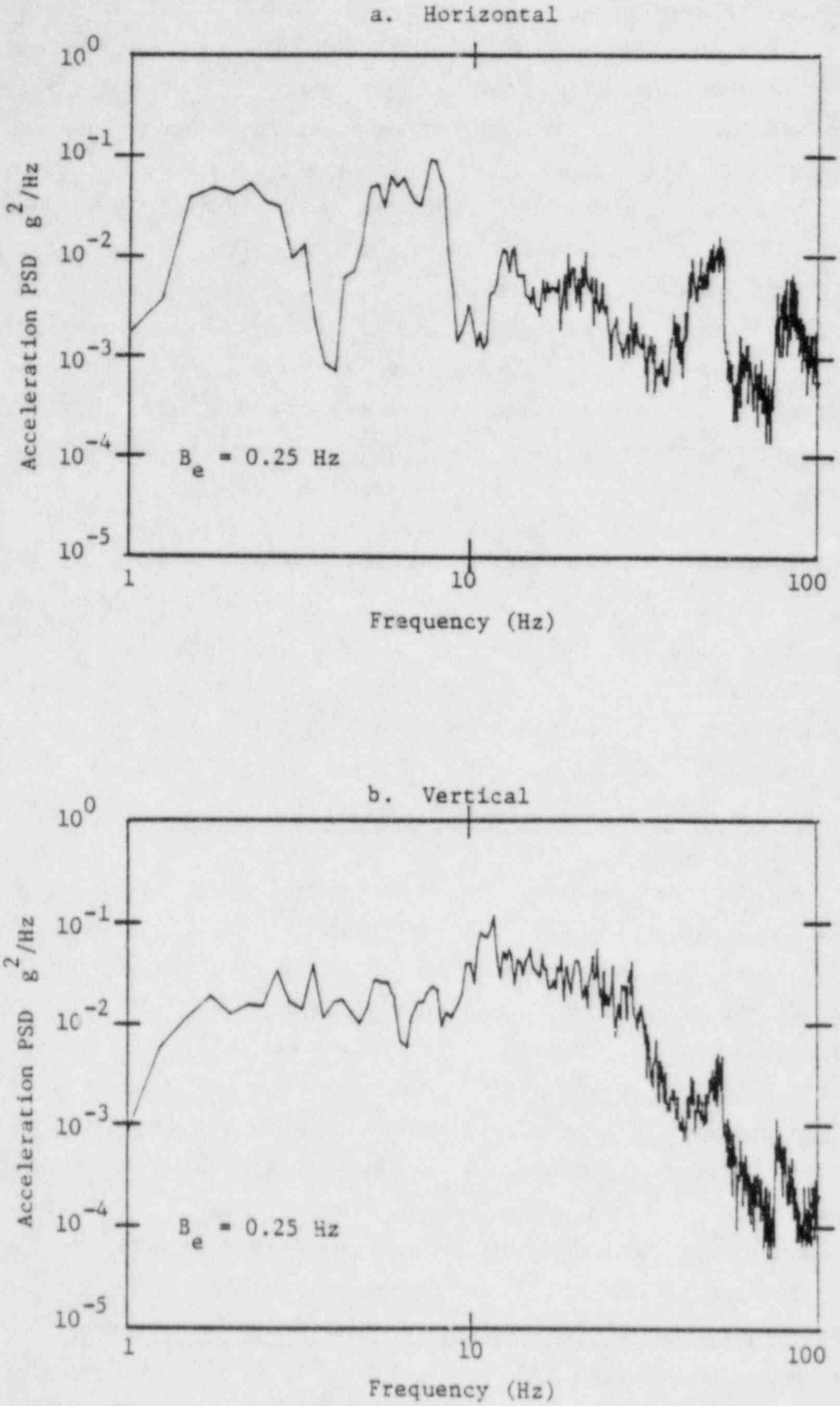


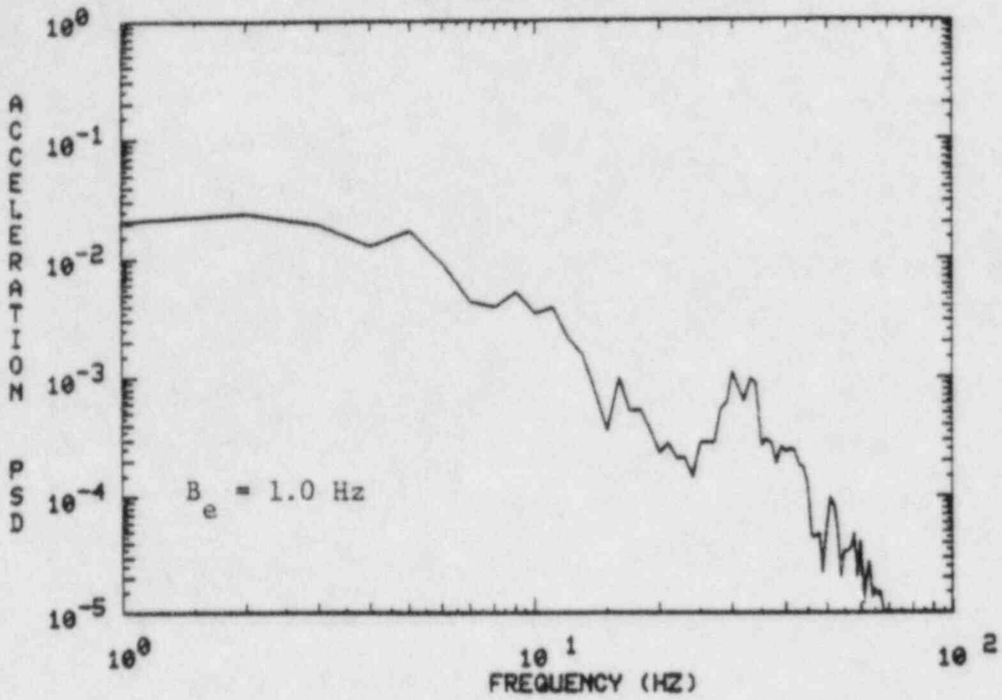
Figure 5.3-1 Required PSD for Yarway

5.3.2 Electrica... Assembly

The case of the requalification of an assembly and devices mounted on the assembly will now be considered. For assembly level testing it is important to consider the differences in frequency content between the acceptable fragility function and the new requirements. This difference is usually easiest to recognize with the data in PSD form. Since functionality is influenced by acceleration at the device locations, any significant shift in the frequency content of excitation may result in erroneous conclusions when comparing excitations to the assembly, rather than to the device. That is, the transfer functions relating excitation and device location accelerations must also be considered. If the excitation frequencies are shifted, such that the resonant frequencies will be subjected to a reduced excitation, care must be used in interpreting the results. In this case it may be necessary to compute the fragility ratios on a device level.

The acceptable fragility function for excitation of the electrical rack assembly are given in Figures 5.2-9 and 5.2-10. These are derived from broadband earthquake simulation testing. First consider requalification to a constant level sinusoidal excitation at 0.1 g's peak input (constant level PSD at 0.01 g^2/Hz) from 1 to 33 Hz. Comparing these results to Figure 5.2-9 indicates that requalification is not possible because the acceptable fragility function falls below 0.01 g^2/Hz above 5 Hz. This would indicate that failure is possible. On the other hand, from actual tests at a limited number of frequencies it has been shown that failure does not occcur as a result of 0.1 g's sine dwell testing. Therefore the acceptable fragility function is conservative and additional testing would be required for requalification. Now consider the case of requalification to a different broadband random excitation. Runs 003 and 005 (Reference [5]) have the same RRS (Reg. Guide 1.60 with a ZPA of 1.0 g's) but different specification on the accuracy to which the TRS matches the RRS. Run 003 has a closer tolerance while Run 005 has no criteria, and the response was generated using excessive low frequency (below 10 Hz) excitation and little excitation energy above this frequency. If the RRS (or PSD) for these two runs were used, both would be acceptable. If on the other hand the measured PSD's were used, Figures 5.3-2 and 5.3-3 respectively, for comparison, Run 003 would be acceptable and Run 005 would show

a. Horizontal



b. Vertical

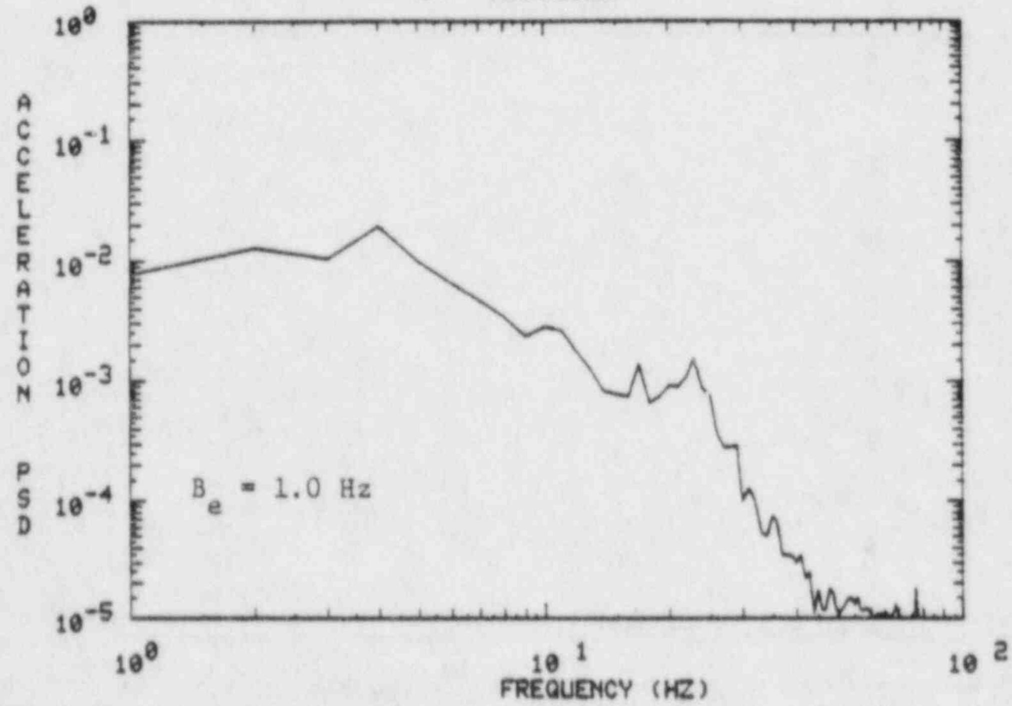
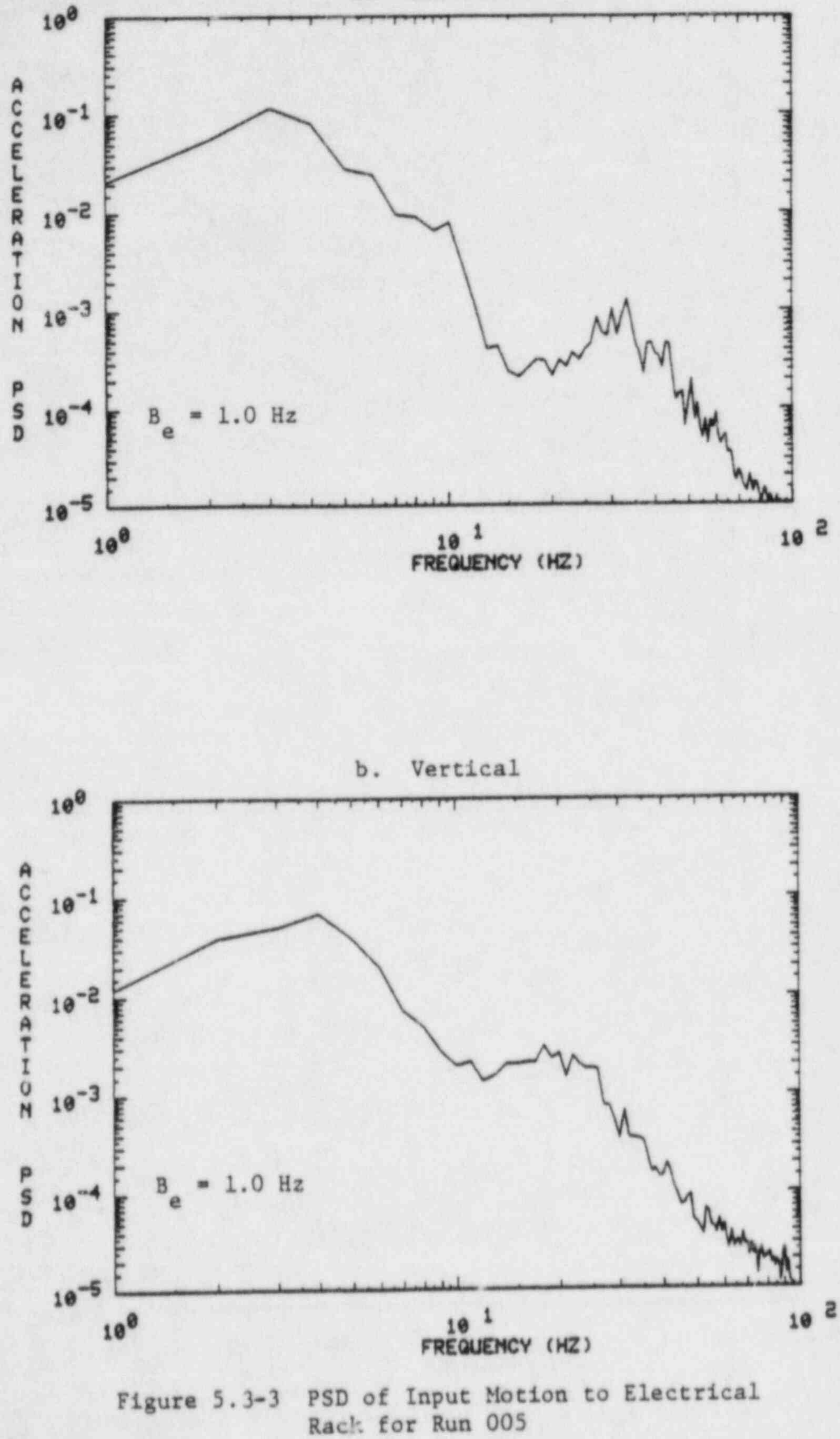


Figure 5.3-2 PSD of Input Motion to Electrical Rack for Run 003

a. Horizontal



b. Vertical

Figure 5.3-3 PSD of Input Motion to Electrical Rack for Run 005

a possibility for failure. In actual testing chatter was noted for Run 005 and not for Run 003, which can be used as a verification of the results. Similar results were noted when comparing Runs 002, 004 and 006, which correspond to an extended Reg. Guide 1.60 excitation. In this case Run 004, with the closest tolerance was the only one for which no failure occurred, and the results reemphasize the importance of a close matching of the TRS and RRS.

These results are based on using the PSD for both the acceptable fragility function and the required excitation levels. The TRS's could have also been used to arrive at similar conclusions. However, as noted in an earlier section, test conditions often result in higher ZPA levels than required. This can mask the true nature of the signal and its influence on the test item. The PSD is a better indication of the energy associated with the excitation and should be used where possible.

It is now necessary to look at the use of assembly testing results to obtain information on a requalification on a device level. For a flexible structure the acceleration of each device location may be different due to structural resonances. As noted earlier if there is significant differences in the frequency content of the excitation between available resets and required levels, requalification may need to be done on a device by device level. It is first necessary to develop an acceptable fragility function for the device locations using either the measured PSD (Figure 5.2-11), or that calculated using the as-tested transfer function (Figure 5.2-13). If these are compared to the measured PSD for Runs 003 and 005 at this location, both would indicate the possibility of failure (Figures 5.3-4 and 5.3-5). As noted earlier failure was noted during Run 005 and not during Run 003. It is important to remember that an indication of possile failure when no failure was observed is a conservative result. Problems would be encountered if the procedure did not predict a failure when one occurred.

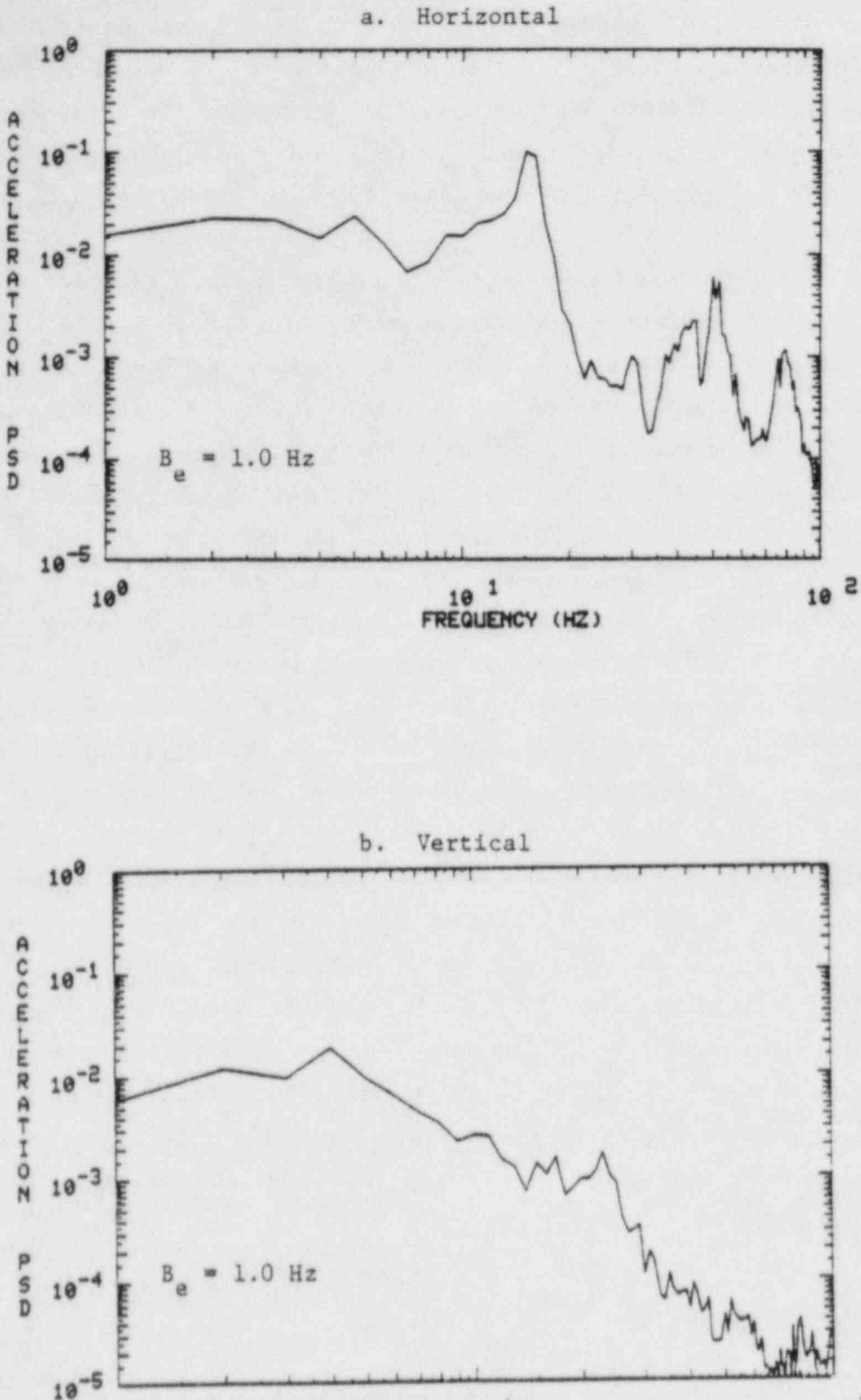
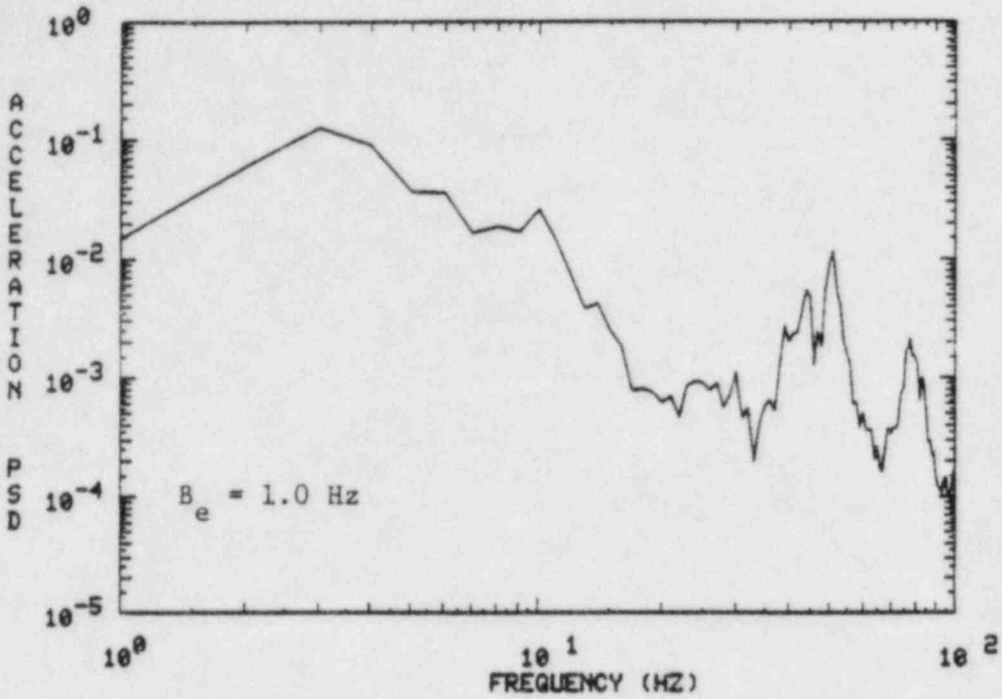


Figure 5.3-4 PSD for Yarway Position on Electrical Rack for Run 003

a. Horizontal



b. Vertical

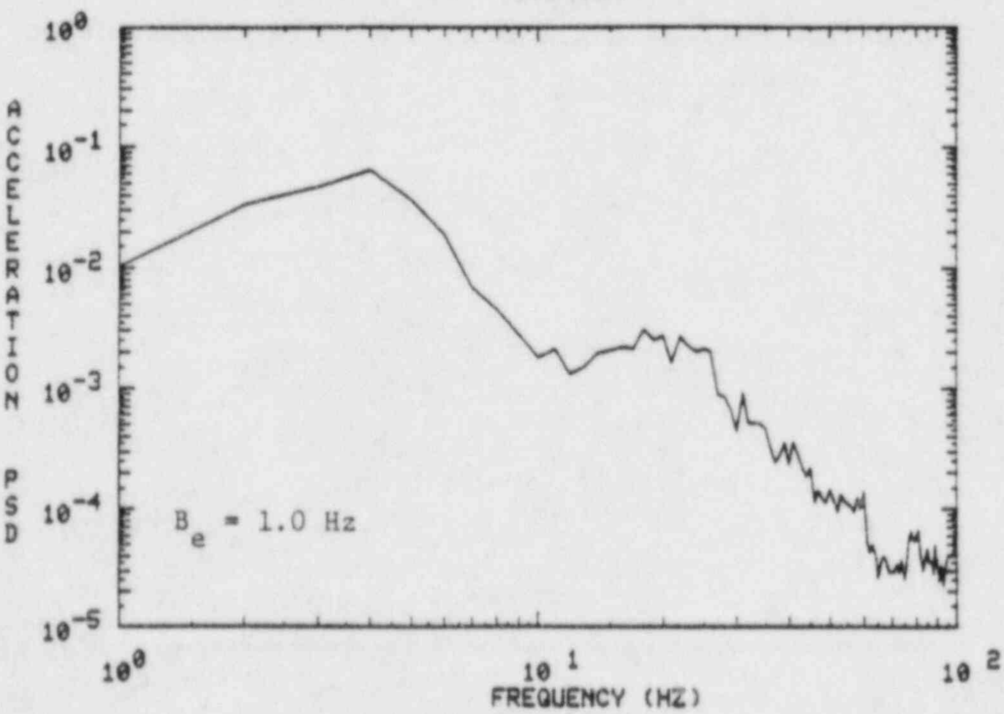


Figure 5.3-5 PSD for Yarway Position on Electrical Rack for Run 005

6.0 SUMMARY AND CONCLUSIONS

A general methodology has been developed for correlating various procedures that may be used to qualify nuclear plant equipment to seismic excitation. Specifically, the type of seismic motion simulation for one qualification can be compared directly with another that may be quite different in character. The fundamental basis for the comparison lies in the use of a vibrational equivalence concept, which allows a damage comparison between the two motions. Absolute damage is understood to occur at the fragility level for the given item, which may fail in an arbitrary manner. Vibration equivalence of the two different motions is understood to be a state whereby each motion produces the same proportional amount of damage relative to the fragility level.

The developed method can be applied for comparison of all known seismic motion simulations that have been used in the past. Therefore, it should be applicable to comparing the qualification of any previously envoked procedure to any currently recommended one. However, some judgement must be used in a specific application, the details of which may vary with each case. Generally, the results of a previous qualification are used first to establish some form of an approximate or acceptable fragility function. Then, the requirements of the newer specification are compared to this function to determine whether a greater or less severe test is implied. In some cases a more accurate fragility function may need to be established in order to provide a final determination of the comparison. In this event, it may be more practical to consider a complete new requalification.

It is surmised that much of the previously qualified equipment will be able to be requalified to new criteria by the analytical method developed. Our basis for this belief is that many qualification tests prior to 1975 included sine wave and sine beat excitations of some form or another. The relative damage severity ratio D_{SR}, also developed in this work and shown to be equivalent to results developed by previous researchers, clearly indicates that such motions produce significantly more potential damage than do typical random motion simulations that have been more generally used after 1975. This is especially true for ground level simulations. This opinion was generally held by many qualification engineers prior to this study, but only the present results allow an absolute determination of a final answer to the question in terms of the damage fragility ratio D_{FR}.

A further useful result of the present work has been an indication of the relationship among several of the various severity or intensity factors that have been proposed in the past. Many of these factors can be used as parameters for comparing qualifications in terms of the damage fragility ratio D_{FR}. However in order to avoid confusion, it is recommended that hereafter the comparisons be carried out on the basis of some standardized parameter, such as response spectrum or PSD. It is the authors' opinion that either of these parameters may be used effectively, although the PSD shows advantages over the TRS in many cases where relatively high unwanted ZPA's have occurred during the qualification test. Furthermore, the liberal transformation of TRS to PSD and vice versa is recommended as appropriate to provide complementary information in a given case.

Finally, it should be recognized that the inherent use of the fragility function in the developed methodology puts a greater emphasis on the use of this concept. Fragility determination for equipment for its own information sake has been well recognized in the past, but has not generally been included in so-called qualification proof tests. Acquisition of fragility data has only been performed in those cases where the margin of qualification has been sought. Direct use of this information in the present correlation methodology is necessary only for those cases where the approximate approach fails. Therefore, the results of this work should not be construed as an endorsement for wholesale acquisition of fragility information in qualification of new equipment hereafter. On the other hand, we do feel that the expansion of the use of fragility information does warrant an intelligent consideration of such data for design purposes. In this regard, the present work serves to recognize the various ways that fragility can be measured, and to clarify the relationships that exist between the various parameters that may be used for its measurement.

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