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Similarity Principles for Equipment Qualification by Experience

Prepared by D.D. Kana, D.J. Pomerening

Southwest Research Institute

Idaho National Engineering Laboratory
EG&G Idaho, Inc.

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Prepared by
D.D. Kana, D.J. Pomerening

Southwest Research Institute
San Antonio, TX 78284

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EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, ID 83415

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ABSTRACT

A methodology is developed for seismic qualification of nuclear plant equipment by applying similarity principles to existing experience data. Experience data are available from previous qualifications by analysis or testing, or from actual earthquake events. Similarity principles are defined in terms of excitation, equipment physical characteristics, and equipment response. Physical similarity is further defined in terms of a critical transfer function for response at a location on a primary structure, whose response can be assumed directly related to ultimate fragility of the item under elevated levels of excitation. Procedures are developed for combining experience data into composite specifications for qualification of equipment that can be shown to be physically similar to the reference equipment. Other procedures are developed for extending qualifications beyond the original specifications under certain conditions. Some examples for application of the procedures and verification of them are given for certain cases that can be approximated by a two degree of freedom simple primary/secondary system. Other examples are based on use of actual test data available from previous qualifications. Relationships of the developments with other previously-published methods are discussed. The developments are intended to elaborate on the rather broad revised guidelines developed by the IEEE 344 Standards Committee for equipment qualification in new nuclear plants. However, the results also contribute to filling a gap that exists between the IEEE 344 methodology and that previously developed by the Seismic Qualification Utilities Group. The relationship of the results to safety margin methodology is also discussed.

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SUMMARY

The current trend in the seismic qualification of equipment is to allow methods other than rigorous analysis and testing on each particular candidate component. Considerable effort is being made to develop methodologies that will continue to ensure safety and will support qualification of whole classes of candidate items based on either experience of previous testing or effects of actual earthquakes on similar equipment.

The United States Nuclear Regulatory Commission (USNRC), Office of Nuclear Regulatory Research has been focusing research efforts toward improving the appropriate guidelines for seismic qualification to ensure that a clear basis is established for verifying the integrity of equipment. The latest revisions of IEEE 344 and the American Society of Mechanical Engineers (ASME) draft standard on seismic qualification of mechanical equipment demonstrate the need for improved guidelines. These standards provide for qualification by using experience data of similar equipment but offer little guidance for establishing qualification when using the method. The purpose of the research described in this report is to provide a basis on which similarity can be established, and to provide practical examples of the use of the methodology. The research also identifies how the methodology could be extended for plant safety margin evaluation.

The principle of similarity among components is based upon comparison of dynamic characteristics of excitation, dynamic characteristics of the component physical structures, dynamic responses of the structures, or combinations of these areas. Qualification of an equipment item is demonstrated when any two of the areas compare favorably. Excitation similarity includes establishment of approximate waveform similarity based upon the ratio of response spectrum peak acceleration to zero period acceleration (ZPA). This is based upon the results of a study evaluating this ratio for typical test waveforms as well as those of different earthquakes.

Procedures for establishing physical similarity include comparison of the following:

1. Assumption of the most probable mode of malfunction.

2. Determination of the critical location on the support structure whose dynamic response most probably affects the malfunction.

3. Establishment of a critical transfer function by test, analysis, or experience between the support structure's excitation point and the determined critical location.

4. Development of a critical frequency range over which critical transfer functions are compared.

5. Assurance that the peak magnitude of the candidate item's critical transfer function is not larger than those of the experience data base.

The comparison of dynamic responses is the ultimate basis of physical similarity. It includes comparison of component functionality and is related to component fragility through the typically dominating role of the candidate device equipment transfer function.

Applications of these procedures allow such practical efforts as the development of composite qualification response spectra for groups of equipment, demonstration of qualification by using similarity, and extension of qualification spectra beyond their previously existing levels and ranges. Examples of such usages with actual test records, as well as with hypothetical two degree-of-freedom systems show more clearly the procedural steps to be used.

The qualification methodology essentially uses the approach currently being supported by the Electric Power Research Institute (EPRI), which develops composite spectra called Generic Equipment Ruggedness Spectra

(GERS) for which classes of equipment are qualified. The methods of this report provide additional guidance to the GERS approach by describing in more rigorous detail a process of developing a composite spectra. Once a composite spectrum for a specified class of equipment is developed, it contains the spectral values utilized to form the High Confidence of Low Probability of Failure (HCLPF) acceleration values for that group of equipment. HCLPF values can subsequently be used as input to the plant seismic safety margin evaluation.

A major concern lies in the detail to which physical similarity must be established, i.e., to what detail the critical transfer function must be established. It is expected that resonance search data from previous tests typically constitute sufficient information for estimation of critical transfer function. When lacking this information, estimates of the transfer function must be made using mass and stiffness properties based upon known information.

Care should be exercised in generalizing the results to other conditions than considered here such as: (1) malfunctions resulting from other than peak response accelerations, (2) certain conditions of modal and cross-axes interaction of device and support structure, and (3) the possible condition in which the critical transfer function is associated with a secondary device rather than the support structure.

To provide a valid qualification, specific information which must be documented on compared components includes:

1. Identification of the type of equipment which forms the data base and general physical characteristics of each item.

2. Identification of the most probable mode of malfunction.

3. Evidence of a critical transfer function in some appropriate form which is related to the probable mode of malfunction.

4. A composite spectrum from a similar class of previously qualified equipment and constituent spectra of that composite.

Using this information to apply the procedures of this report to develop a proper assertion as to how any candidate item satisfies the identified comparisons would meet the requirements of IEEE 344, and would therefore, constitute qualification by similarity.

FOREWORD

For the past several years the Office of Nuclear Regulatory Research of the Nuclear Regulatory Commission (NRC) has focused some of its research efforts towards improved methodology for equipment seismic qualification.

Since 1972, seismic qualification of electrical and mechanical equipment in safety-related systems has generally relied upon IEEE 344 for direction in the methods and details of qualifying components. Recently, the American Society of Mechanical Engineers (ASME) has also been drafting seismic qualification guidelines explicitly for pumps and valves in safety systems. Both sets of guidelines offer the option of qualification by previous experience with similar components, but offer little detail in this method of qualification.

The NRC rule for the resolution of Unresolved Safety Issue A-46, Seismic Qualification of Equipment in Operating Plants, allows qualification of equipment by experience by comparing the candidate components for qualification with a data base consisting of broad classes of equipment in both nuclear and nonnuclear facilities that have undergone actual seismic events. The comparisons are based on similarity of the physical structure and earthquake amplitude levels. Electric Power Research (EPRI) has extended this approach to qualification of new equipment by use of Generic Equipment Ruggedness Spectra (GERS) for broad classes of equipment. GERS are composites of selected tests and actual earthquake response spectra for groups of previously qualified equipment judged to be physically similar. Qualification is established by selecting the group for the candidate equipment and verifying the required spectra is enveloped by the GERS. The NRC has contracted EG&G Idaho at the Idaho National Engineering Laboratory (INEL) to oversee the development of a methodology which would enhance the IEEE and ASME guidelines in the area of seismic qualification by experience and, ultimately, to contribute to the methodology for establishing plant safety margins. The Southwest Research Institute (SWRI) was subcontracted by EG&G Idaho to perform this methodology development.

The efforts of the SWRI staff have been oriented toward the utilization of the basic GERS approach for qualification by similarity and to provide a more rigorous basis and additional guidance for its implementation. The recommended method uses test and seismic experience data and includes the estimation of transfer functions of supporting equipment for candidate equipment recognizing the majority of seismic qualifications are dependent upon support equipment response. This contribution to the seismic qualification of equipment will aid in providing a methodology that lends more confidence in arriving at similarity.

SPECIAL GLOSSARY AND NOTATION

Critical device. A safety-related device whose malfunction produces the lowest possible fragility level of excitation for an equipment item.

Composite spectrum. A combined response spectrum which is formed within the envelope of two or more individual (or constituent) spectra, so that its excitation effect is likely to produce equal or less response than any one of the individual spectra.

Candidate equipment. Equipment that is to be qualified by experience or other methods.

Device. A secondary component attached to a primary structure.

Equipment. Electrical or mechanical components comprised of a primary structure which may or may not include secondary devices.

Primary structure. The major structure for an equipment item whose response alters the excitation environment experienced by attached devices or influences structural integrity.

Elevated location response. Dynamic response which occurs at some location in a primary structure as a result of base motion excitation (usually the critical location).

Physically identical equipment. Different equipment items whose dynamic response and functional (operational) characteristics are identical over the entire frequency range of interest.

Physically similar equipment. Different equipment items whose dynamic response and functional (operational) characteristics are approximately equal within a specified frequency increment. Alternatively, equipment whose fragility functions are nearly equal in the most sensitive frequency increments.

Reference equipment. Previously qualified equipment whose dynamic and functional (operational) characteristics are well known, and whose qualification data are available.

Spectrum extension. A method whereby the qualification of an equipment item can be extended to other response spectra that are not enveloped by the original qualification spectrum.

$F_f(f)$ — Failure mechanism fragility function. The level which is achieved by the failure mechanism response function $R_f(f)$ when malfunction initially occurs in an equipment item.

f_c — Critical frequency. Frequency at which the critical transfer function peak value (resonance) occurs.

Δf_c — Critical bandwidth. Bandwidth of critical transfer function at 1/2 power point (i.e., at 0.7 of the peak value).

Δf_{cc} — Composite critical bandwidth. Composite frequency band comprised of critical bandwidths from two or more critical transfer functions and the frequencies in between them (measured at 0.7 peak value of critical transfer functions included).

Δf_{opt} — Optimum bandwidth. Optimum bandwidth for selection of Δf_{cc} on a composite spectrum. Alternately, the bandwidth within which multiple spectra are most similar.

$H_p(f)$ — Critical transfer function. Frequency response function between the excitation and a critical location on the primary structure whose response can be related directly to the function/malfunction of the equipment.

$H_{pi}(f_{ci})$ — Critical peak value. Value of critical transfer function for equipment item-i at the critical frequency f_{ci}.

$M_f(f)$ — Failure mechanism transfer function. A hypothetical transfer function which would describe an equipment function (operation) in terms of motion response at the critical location on the primary structure.

$R_x(f)$ — Excitation response spectrum. Response spectrum at excitation point of equipment.

$R_x^*(f)/ZPA$ — Maximum spectral amplification factor. Ratio of maximum spectral response to ZPA for a given response spectrum.

$R_f(f)$ — Failure mechanism response function. A hypothetical function which describes the frequency response of the function (operation) of an equipment item.

$R_y(f)$ — Elevated location response spectrum. Response spectrum for motion at elevated location on the primary structure (usually the critical location).

β — Response spectrum damping ratio. Damping ratio for which response spectrum is calculated.

ζ_n — Equipment damping ratio. Damping ratio for nth mode in equipment item.

ζ_{ci} — Critical equipment damping. Damping ratio for critical mode in equipment item-i.

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FIGURES

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SIMILARITY PRINCIPLES FOR EQUIPMENT QUALIFICATION BY EXPERIENCE

1. INTRODUCTION

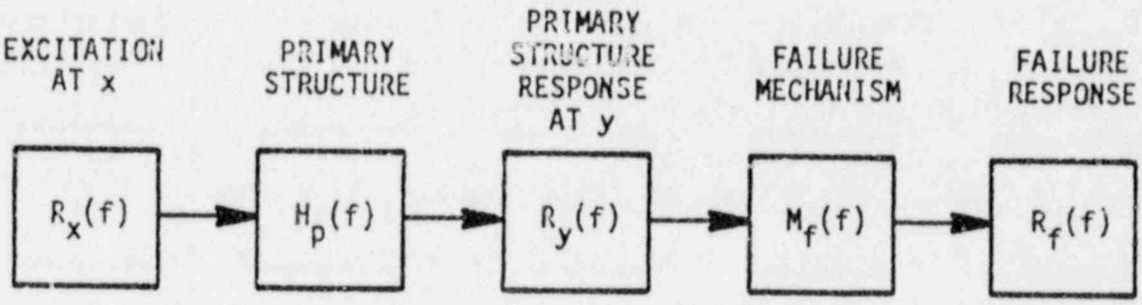
Since about 1971 and certainly since 1975, seismic qualification of equipment for use in nuclear power plants has generally been accomplished by means of analyses, tests, and/or combined test and analysis methods [1]. A large volume of qualification data has been generated from this effort. The current trend is to compile the available data from this experience, as well as that from nuclear and nonnuclear plants that have been subject to actual earthquake events, and develop a formal methodology for qualification based on such experience data. Obviously, a reduction in time schedules and costs required by the above conventional methods are sought. The general guidelines for development of experience data methodology have already been formulated [2], and are based on the concept of qualification by similarity. However, more specific guidance is necessary for the approach to be practical and to avoid its potential misapplication. The purpose of this report is to present a basis from which the similarity principals originate, more specific similarity methodology, practical examples of the use of that methodology in qualification by experience, and a relationship for the methodology to safety margin applications.

The general approach to qualification by similarity [2] includes development of an argument that qualification of a new equipment item follows a-priori because of appropriate similarities between certain data which describes the equipment and its intended environment, and that which already exists in an experience data base. Herein, similarity will be denoted by the symbol $\approx$, which also means "approximately equal to" in a designated frequency bandwidth, for certain parameters of the problem. Appropriate similarities can be defined according to the dynamic characteristics of a) the seismic excitation, b) the physical system (equipment), c) certain dynamic responses of the system, or d) combinations of these characteristics. Details of the approach for a specific case, including the degree of similarity necessary, will depend on the nature of the equipment and the existing data. However, certain fundamental principals must be applied in any case. A development and discussion of these principles is presented herein, along with more specific steps which lead to practical applications. General terminology follows that for Reference [2], except for some new terms defined herein.

2. FRAGILITY BASIS FOR SIMILARITY

Herein, we postulate that the ultimate basis for similarity principles resides in the general concept of fragility for an equipment item [3], as depicted in Figure 1a. That is, the fragility function $R_F(f)$, which describes failure or malfunction of an item in terms of excitation parameters, is dependent on characteristics of the excitation $R_x(f)$, a particular primary structure critical transfer function $H_p(f)$, and the nature of the failure or malfunction mechanism $M_f(f)$. Note that herein time is included implicitly as a given number of event durations, so that all indicated parameters are functions of frequency only. Furthermore, the critical transfer function $H_p(f)$ pertains to a primary structure location whose dynamic response can be directly related to the malfunction of the equipment. Likewise, in accordance with procedures defined in Reference [2], the fragility response spectrum $R_F(f)$ corresponds to the elevated level approached by the excitation represented by $R_x(f)$, when the failure response corresponding to $R_f(f)$ approaches the failure mechanism fragility function $F_f(f)$. Of course, $R_f(f)$ and $F_f(f)$ are never determined explicity in a qualification, but instead are inherently included in the observation of the function/malfunction behavior of the equipment. They are included in Figure 1a merely as a convenience for conceptually describing the fragility behavior of equipment.

To put these definitions into perspective, a specific example of the fragility concept is shown in Figure 1b. An electrical cabinet is excited in a given direction by an acceleration time history $a_x(t)$, whose response spectrum is $R_x(f)$. The interior panel of the cabinet contains several devices whose functions are safety-related to the operation of a nuclear plant. As the amplitude of the excitation is increased on each of several successive test runs, the primary structure response $a_y(t)$ at the critical device location also increases via the critical transfer function $H_p(f)$. All of the safety-related devices continue to function properly through their functional mechanisms $M_p(f)$, until eventually at some excitation level one of the devices (which is designated as the critical device) malfunctions. The excitation response spectrum $R_x(f)$ for this



No Failure Occurs For:

$$R_f(f) < F_f(f)$$

Failure Occurs For:

$$R_f(f) \geq F_f(f)$$

Fragility Boundary Definition:

$$\text{For } R_f(f) = F_f(f) \Rightarrow R_x(f) = R_F(f)$$

$R_x(f)$	Excitation Response Spectrum at Point x
$H_p(f)$	Primary Structure Critical Transfer Function
$R_y(f)$	Primary Structure Response Spectrum at Point y
$M_f(f)$	Failure Mechanism Transfer Function (Not determined explicitly)
$R_f(f)$	Failure Mechanism Response Function (Not determined explicitly)
$F_f(f)$	Failure Mechanism Fraglity Function (Not determined explicitly)
$R_F(f)$	Excitation Fragility Response Spectrum

Figure 1a. Conceptual definition of equipment fragility for time-independent failure.

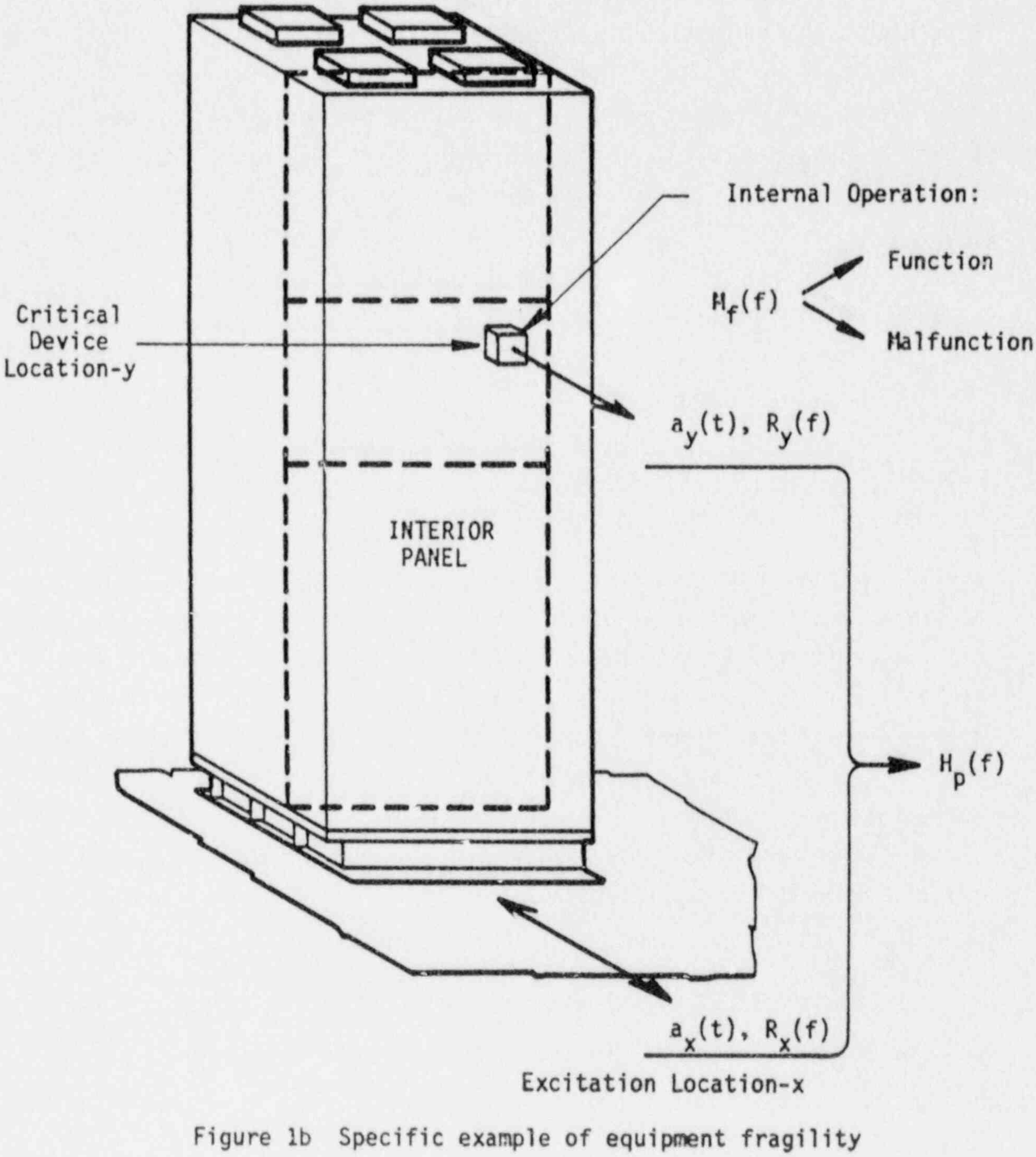


Figure 1b Specific example of equipment fragility

excitation level is further designated as the fragility response spectrum $R_F(f)$. Note that the malfunction is not determined by a measure of $M_f(f)$ or $R_f(f)$ per se, but simply by an observation of a related response, such as relay chatter or trip.

Although response spectra are used for motion descriptions in Figure 1a, power spectra can also be used. For example, if the critical transfer function $H_p(f)$ is linear, one can write:

$$a_y^* = 2\zeta_n \left| H_p(f_n) \right| R_x(f_n) \quad (2.1)$$

or

$$G_y(f) = \left| H_p(f) \right|^2 G_x(f) \quad (2.2)$$

where $| \; |$ denotes magnitude of the enclosed function. These two equations are expressed in forms that can be useful for both test and analysis purposes. At this point, they are used only generically to lend credence to the fragility concept displayed by the diagram in Figure 1a. However, they are often used directly for analytical qualification or support of combined analytical and test qualifications. Some additional comments about the specific forms of these equations are appropriate to provide a further understanding of some limitations that apply to the equipment fragility concept as described in Figure 1a.

In Equation (2.1), a_y^* is the peak acceleration that occurs at the critical response point y. The relationship is valid, providing that a single mode with resonance frequency f_n and modal damping ζ_n dominate the primary structure response. This equation, which includes the critical transfer function value $H_p(f_n)$ at frequency f_n, is derived in Reference [4]. It is an alternate form of the more familiar response prediction equation which includes a modal participation factor, typically used by analysts. The modal participation factor γ_n which corresponds to a single point input for mode-n, and the corresponding critical transfer function value $H_p(f_n)$, are related by:

$$\gamma_n = \frac{2\zeta_n}{\phi_n(y)} \left| H_p(f_n) \right| \tag{2.3}$$

where $\phi_n(y)$ is the mode-n eigenvector (which results from a typical modal analysis) evaluated at the response point in question. Furthermore, if more than one mode is present, then some combination of the multimode effects must be employed. In Equation (2.2), $G_y(f)$ is the response PSD (power spectral density) at point y, while $G_x(f)$ is the excitation PSD that corresponds to the excitation spectrum, $R_x(f)$. Furthermore, if the excitation has a Gaussian distribution which infers a given peak/RMS ratio, then the response is also Gaussian and infers approximately the same peak/RMS ratio. Extensive development and use of Equation (2.2) is given in Bendat and Piersol [5], and various other texts.

It may be noted that Equation (2.1) is not a direct relationship for calculation of input and output response spectra, as Equation (2.2) is for power spectra, in conformance with Figure 1a. In fact, no such simple direct relationship exists for response spectra. The relationship must be used 1) indirectly by a time history method, whereby a response spectrum $R_y(f)$ is produced from a calculated response time history; or 2) indirectly whereby Equation (2.2) is used to calculate a response power spectrum $G_y(f)$, and this parameter is subsequently transformed to the response spectrum $R_y(f)$ [6].

If the nature of the primary structure is nonlinear (which occurs to some degree in most equipment), Equations (2.1) and (2.2) do not apply directly, but are only approximations to the actual governing equations. Nevertheless, approximate linear evaluations are almost always used in analysis, since nonlinear approaches very quickly become impractical, except for special cases. Thus, quasi-linear developments which include evaluation of $H_p(f)$ at a given response level may be appropriate when $H_p(f)$ is a function of excitation amplitude. Furthermore, analytical expressions for $R_y(f)$, $M_f(f)$, and $R_f(f)$ may be very complex and, in fact, are never determined explicitly. Also, $M_f(f)$ represents a malfunction process that can be especially varied in the diversity of equipment used in nuclear plants. Usually, this process will apply to some critical device that is attached at an elevated position on the primary structure, as presented in Figure 1b. However, it could also represent the stress level at some critical location in the primary structure itself. Some examples of how a critical process or device can malfunction are: exceeding threshold response for displacement, velocity, acceleration or stress; relay chatter or trip, etc. Thus, $M_f(f)$ may be linear, nonlinear, or of logic form, which is difficult to write as a mathematical relationship. Nevertheless, the general concept depicted in Figure 1a is applicable in any case, and will be used in developing similarity principles without having to establish any mathematical relationships. In doing this, fragility is inherently included by consideration of the function/malfunction of the equipment, rather than by development of exact fragility functions.

The use of the critical transfer function $H_p(f)$ for the primary structure is inherent in all qualification scenarios by use of similarity principles to be used in this report. In Figures 1a and 1b, these transfer functions have been defined as those relative to a base motion excitation, which typically may have been acquired from experimental resonance searches in previous qualifications. Herein, all applications and examples will be based on this type of transfer function, since it corresponds directly to excitation by earthquake ground or floor-level motion. However, it is apparent that the similarity procedures outlined in this report can also be carried out by means of base-fixed transfer functions. This type of transfer function is typically measured by in-situ tests, or can readily be developed by analytical methods. Note that either type of transfer function can be used, but they cannot be mixed in the process of carrying out similarity arguments.

Different variations of Figure 1a will be drawn to represent different qualification scenarios, each of which relies on one of the three forms of similarity to be defined, or some combination of them. However, they must all rely on fragility as the basis for establishing qualification, no matter which form of similarity is employed. This basis for similarity will be referred to repeatedly in the discussion to follow. Furthermore, when used as a basis for establishing qualification for a proof test condition, of course actual failure or malfunction does not occur, so continuity of equipment function becomes the criterion. Therefore, the use of generic or elevated-level qualification data as lower bound estimates for fragility [3] becomes an appropriate consideration, and the concept shown in Figure 1a still applies.

3. TYPES OF SIMILARITY

A broad definition is given in Reference [2] for three types of similarity that are appropriate for use in equipment qualification. In this section, portions of these broad definitions will be paraphrased, and further developed into a correspondence with the general concept of equipment fragility defined in Figure 1a. Each development will include, first, a definition of corresponding equality which, although it may be obvious, is the principle on which heretofore equipment qualification methodology is based. Then, follows a corresponding definition of similarity, so that the essential differences in equality and similarity can readily be established.

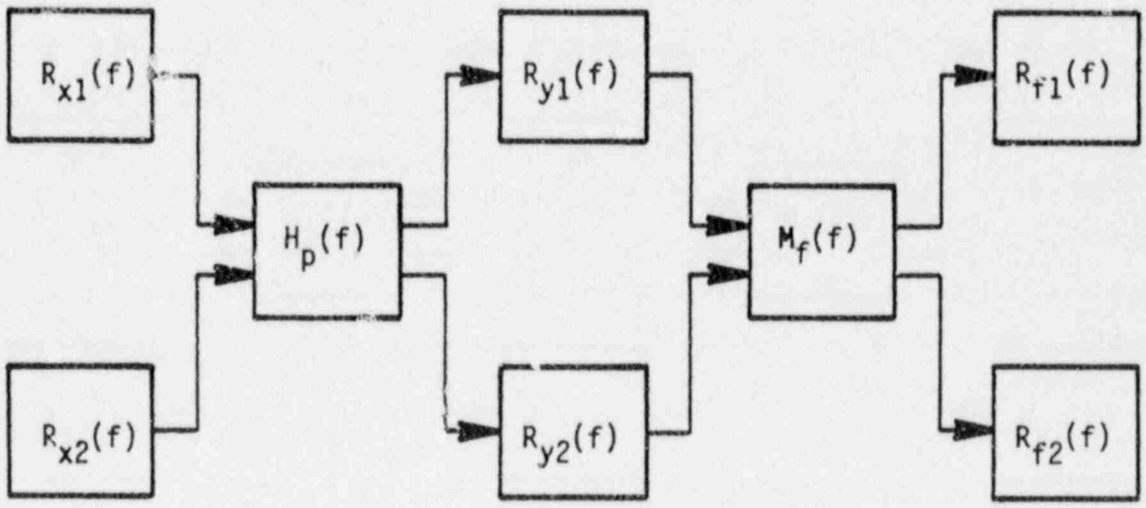
3.1 Excitation Similarity

3.1.1 General Definition

"Similarity of excitation constitutes likeness of parameters such as spectral characteristics, duration, directions of excitation axes, and location of measurement for the motions relative to the equipment mounting,"[2]. Figure 2 provides an elaboration of this definition for application to a typical equipment qualification scenario, where a single equipment item with critical transfer function $H_p(f)$ is alternately subjected to two different excitations corresponding to $R_{x1}(f)$ and $R_{x2}(f)$. However, first consider this diagram as a representation of the current approach to qualification of a single equipment item not previously qualified, and then the similarity concept can be shown to be a direct extension of that approach. That is, in Figure 2, consider $R_{x1}(f)$ to be a RRS (Required Response Spectrum) that is prescribed for qualification of the item. If R_{x2} is the TRS (Test Response Spectrum) for a test, then the current enveloping requirement is:

$R_{x2}(f) \geq R_{x1}(f)$ for all f.

The requirement is that not only excitational equality, but conservative similarity of excitation must exist at all frequencies.



Given $H_p(f)$ and some indication of $M_f(f)$,

Excitational Equality:

If $R_{x1}(f) = R_{x2}(f)$,

Then $R_{y1}(f) = R_{y2}(f)$ and $R_{f1}(f) = R_{f2}(f)$

so that

$$R_{F1}(f) \equiv R_{F2}(f) \quad \text{for all } f$$

Excitational Similarity:

If $R_{x1}(\Delta f) \approx R_{x2}(\Delta f)$,

Then $R_{y1}(\Delta f) \approx R_{y2}(\Delta f)$ and $R_{f1}(\Delta f) \approx R_{f2}(\Delta f)$

so that

$$R_{F1}(\Delta f) \approx R_{F2}(\Delta f) \quad \text{for given } \Delta f,$$

which means "approximately equal response within a specified frequency range Δf".

Figure 2. Definition of excitation similarity.

Now consider a different practical situation in which the enveloping requirement will be relaxed somewhat. That is, given that a single equipment item has been qualified to excitation $R_{x1}(f)$, what are the dynamic characteristics of excitation $R_{x2}(f)$ that must be similar to $R_{x1}(f)$ so that the item is also qualified to $R_{x2}(f)$? The intent behind the above quotation from Reference [2] becomes much clearer after referring to Figure 2, in which a more precise definition is based on the implied effects that the excitation has on the equipment. That is, the excitation causes some critical dynamic response via the equipment critical transfer function, and this response triggers some form of damage level in the equipment. However in contrast to the above described IEEE 344 requirements in which overall excitational equality is required, excitational similarity is defined whereby two spectra are required to be only approximately equal in <u>certain discrete increments of the frequency range</u>. Thus, a similar excitation is one which produces a similar damage level, even though the excitations are not identical at all frequencies. This can only occur if dynamic characteristics of the equipment also satisfy certain conditions. Therefore, the degree of similarity that must be shown in the excitation characteristics depends on what, if anything, can be <u>predetermined</u> about the equipment critical transfer function $H_p(f)$ and the form of malfunction in the equipment in question. This leads to the definition of physical similarity, which is discussed hereafter. The implication is that two of the three types of similarity are necessary for qualification to be established when excitational identity is not present.

3.1.2 <u>Waveform Similarity</u>

As defined in Figure 2, excitational similarity requires two spectra to be approximately equal within a designated bandwidth Δf, but not outside this band. Intuitively, it is apparent, however, that differences of the spectra outside this band cannot be unlimited. This leads to the concept of waveform similarity, which assures that overall frequency bandwidth is sufficiently similar for two spectra, so that essential dynamic behavior of a system to which the excitation is applied is not changed dramatically outside the frequency band Δf. Therefore, waveform similarity may be assured providing that the ZPA/RMS (Zero Period Acceleration/Root Mean Square) ratio for the two excitations are nearly the same [5].

The RMS value of a waveform can be computed directly from a time history. However, usually only the response spectrum is available in qualification scenarios. The RMS value which corresponds directly to a given response spectrum can be computed by transfer of the response spectrum to a power spectral density, and determining the area under the PSD curve [6]. This RMS corresponds to the strong motion portion of the excitation waveform. However, this process requires use of a digital computer program, and may be more elaborate than appropriate for similarity procedures. Therefore, waveform similarity can be established approximately by comparing the maximum spectral acceleration to ZPA ratio ($R_x^*(f)/ZPA$) for two response spectra. It has been shown in Reference [3] that this amplification factor varies with damping of the oscillator, and the bandwidth of the waveform. For example, at 5% damping, the amplification varies from 10.0 for a steady state sinewave, about 7.5 for a ten cycle per beat sinebeat, to about 2.6 for a random signal which matches a R.G. 1.60 spectrum. Therefore, waveform similarity of two spectra may be approximately assured when the maximum spectral amplification factors are nearly equal. Appendix A of this report includes further support of this approximate approach.

3.1.3 Excitation Axes

The orientation of horizontal excitation is usually specified relative to principle geometric axes, i.e., front-to-back and side-to-side. The direction of excitation can have a significant bearing on the operation of various equipment. This direction of excitation has always been identified for qualifications in the past. Herein, it will be recognized throughout that subsequent use of data from such qualifications will include allowing for proper excitation orientation.

To summarize, when considering excitation similarity, the following specific items must be included:

(1) Frequency distribution (response spectrum or PSD)

(2) Peak amplitude

(3) $R_x^*(f)$/ZPA factor

(4) Time duration

(5) Axes of orientation

(6) Point of application

3.2 Physical Similarity

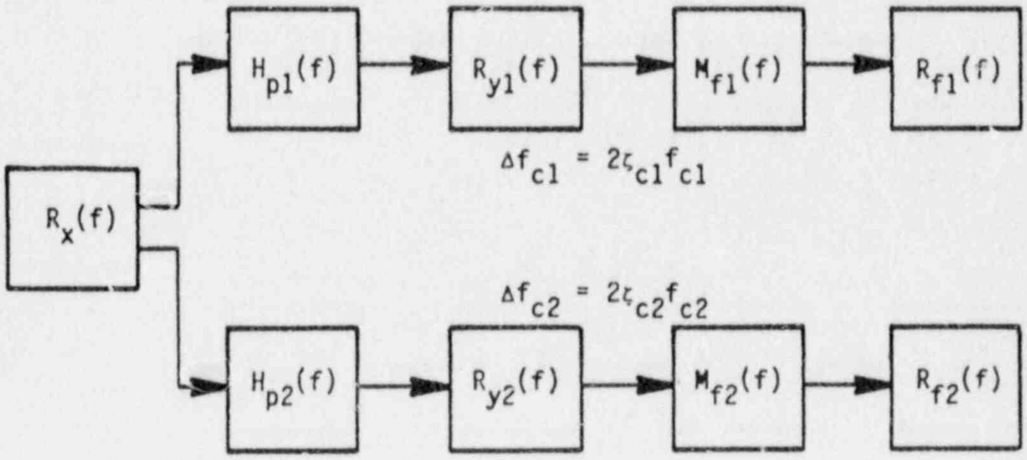
3.2.1 General Definition

"For a complete assemb[illegible] similarity may be demonstrated through comparison of make, mo[illegible]erial numbers, and consideration of dynamic properties and construction. Since the end objective of qualification by the similarity method includes a consideration of the expected dynamic response, a rational approach can be used to establish similarity of dynamic structural properties by an investigation of physical parameters of equipment systems. This can be done by comparing the predominant resonant frequencies and mode shapes," [2].

One explicit method to satisfy the above requirements includes development of transfer functions at locations important to the performance of the system. Therefore, herein, for the purpose of establishing physical similarity, the equipment will be characterized by a critical transfer function $H_p(f)$, which will be determined explicitly; and its failure or malfunction mechanism $M_f(f)$, which will only be determined implicitly (i.e., by a pass/fail observation). This approach is consistent with previous qualification procedures. The approach is shown conceptually in Figure 3, where two different equipment items are subject to the same excitation spectrum $R_x(f)$. The appropriate question becomes, how can the critical transfer functions for the two items best be established and compared, so that their common fragility response (and, therefore, physical similarity) can be established? The approach is outlined in the figure by first defining physical equality in terms of $H_p(f)$ and $M_f(f)$, and this leads to the further indicated definition of physical similarity. Therefore, the differences between the two can readily be distinguished. It may be noted that the definition of similarity indicated in Figure 3 could conceivably be satisfied even though the two equipment items were not similar functionally. That is, one might be an electrical cabinet and the other a valve. However, the most likely practical situation will be where both items are similar in general physical characteristics and function.

Figure 4 is useful to emphasize further how critical transfer functions can conveniently be used to compare directly the dynamic characteristics of different equipment, and to describe the "degree of physical similarity" in that equipment. In accordance with the concept shown in Figures 1 and 3, each equipment item is described by a primary structure critical transfer function $H_p(f)$. The dynamic response of the primary structure at the critical location is judged to be directly associated with the function/malfunction of the equipment. This transfer function may include a single dominant mode, as indicated for each item in Figure 4, or multiple modes. The critical bandwidth Δf_{ci} for each item is a frequency band within which the dominant response occurs. (Obviously, the width of this band is determined by the damping in the equipment and any modal interaction present.) The composite bandwidth Δf_{cc} is defined as the bandwidth between $f_{ci} - 1/2\Delta f_{ci}$ and $f_{cj} + 1/2\Delta f_{cj}$, where f_{ci} is the lowest and f_{cj} is the highest natural frequency present.

If two items had identical critical transfer functions, then they would satisfy physical equality (identity), as described in Figure 3. The amount of difference [i.e., bandwidth Δf_{ci}, center frequency f_{ci}, and magnitude $H_{pi}(f_{ci})$] all determine the degree (i.e., large or small) of



Given $R_x(f)$,

<u>Physical Equality:</u>

If $M_{f1}(f) = M_{f2}(f)$ and $H_{p1}(f) = H_{p2}(f)$,

Then $R_{f1}(f) = R_{f2}(f)$ and $R_{y1}(f) = R_{y2}(f)$

$$\Delta f_{c1} = \Delta f_{c2}$$

so that

$$R_{F1}(f) \equiv R_{F2}(f) \quad \text{for all } f$$

<u>Physical Similarity:</u>

If $M_{f1}(\Delta f) \approx M_{f2}(\Delta f)$ and $H_{p1}(\Delta f) \approx H_{p2}(\Delta f)$

Then $R_{f1}(\Delta f) \approx R_{f2}(\Delta f)$ and $R_{y1}(\Delta f) \approx R_{y2}(\Delta f)$

$$\Delta f_{c1} \approx \Delta f_{c2}$$

with Δf_{c1} and Δf_{c2} both contained in Δf_{cc}

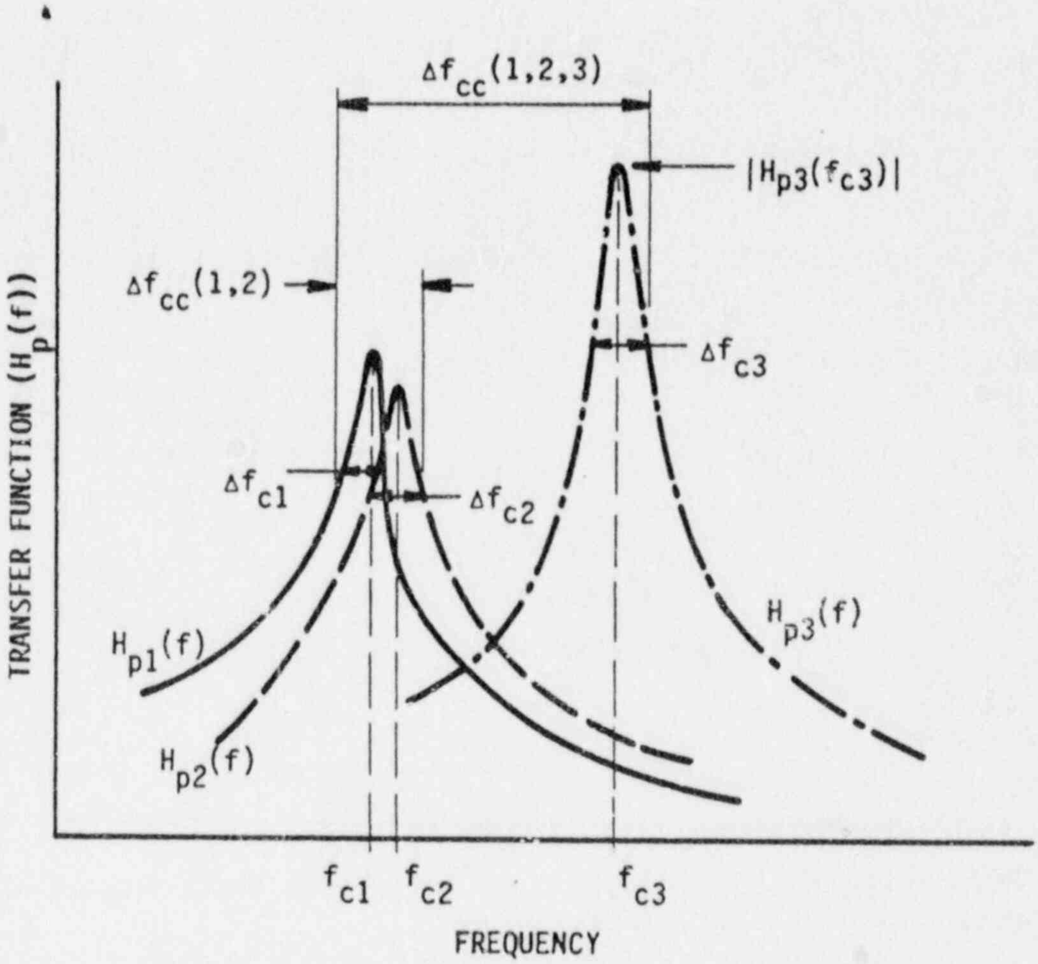
so that

$$R_{F1}(\Delta f_{cc}) \approx R_{F2}(\Delta f_{cc}) \quad \text{for given } \Delta f_{cc}$$

where

Δf_{cc} = Preselected composite critical frequency bandwidth

Figure 3. Definition of physical similarity.



LARGE SIMILARITY: Items 1, 2

SMALL SIMILARITY: Items 1, 3
Items 2, 3

Δf_{ci} is bandwidth at half-power amplitude (i.e., 0.7 peak amplitude)

Figure 4. Degrees of physical similarity.

physical similarity present. Thus, large similarity denotes more nearly identical critical transfer functions for two items. Furthermore, it must be emphasized again that the critical transfer function $H_p(f)$ is not just any dynamic response indicator, but in addition it must correspond to a critical location, whose response is directly associated with the function/malfunction of the equipment. Therefore, this description is totally sufficient, in that it includes all information necessary to describe the dynamic, functional, and fragility characteristics of the equipment, as required by Reference [2].

It may be noted that the indicated definition of physical similarity allows relaxation of the dynamic characteristics to where only approximate (but conservative) equality exists in certain discrete areas of the frequency range. The respective critical frequency f_{ci} is one that would represent the minimum on a narrowband fragility function [or peak of $H_p(f)$], and Δf_{ci} is taken as the frequency bandwidth of $H_p(f)$ at the half-power response level. This selection of Δf_{ci} is relatively arbitrary, but is done to concentrate on a dominant bandwidth in which most of the response occurs. Use of the half-power bandwidth, as indicated in Figure 4, provides a simple relationship with the modal damping and critical frequency, or with the peak magnitude of $H_{pi}(f_{ci})$, as will be indicated shortly. Note also that the composite critical bandwidth Δf_{cc} will be wider than Δf_{c1} and Δf_{c2}, as it must include them both, as indicated in Figure 4. Furthermore, only frequencies, bandwidths, and peak amplitudes of the critical transfer functions enter the essential part of the definition, as will be explained later. The degree of similarity, or extent of such commonality of approximation in frequency bands necessary to establish qualification in a given case also will depend on details of the excitation, as will be described later.

3.2.2 Procedure to Establish Physical Similarity

In order to establish physical similarity between one equipment item (designated as Item 1) and another item (designated as Item 2), the following is one procedure that may be used:

(1) Assume the most probable mode of malfunction for Item 1, and show by experience or deductive reasoning that this mode of failure is essentially alike that of Item 2.

(2) Determine, by experience or deductive reasoning, a critical location on Item 1 whose dynamic response most probably affects the malfunction. Likewise, make this determination for Item 2.

(3) Establish by test, analysis, or experience, a critical transfer function $H_p(f)$ between the excitation point and the critical response point for both items. The degree of detail of this transfer function will vary considerably, depending on the method used and the accuracy of the data available. The most essential information is the critical frequency f_{ci}, the critical bandwidth Δf_{ci}, and the peak magnitude $|H_{pi}(f_{ci})|$ for the critical transfer function. Note that:

$$\Delta f_{ci} = \Delta f \text{ at } 0.7\,|H_{pi}(f_{ci})|$$

which can be obtained from an experimental plot, or $\Delta f_{ci} = 2\zeta_{ci} f_{ci}$ which can be calculated if the modal damping ζ_{ci} is available.

(4) Verify that the critical transfer function peak magnitudes satisfy:

$$|H_{p1}(f_{c1})| \leq |H_{p2}(f_{c2})|$$

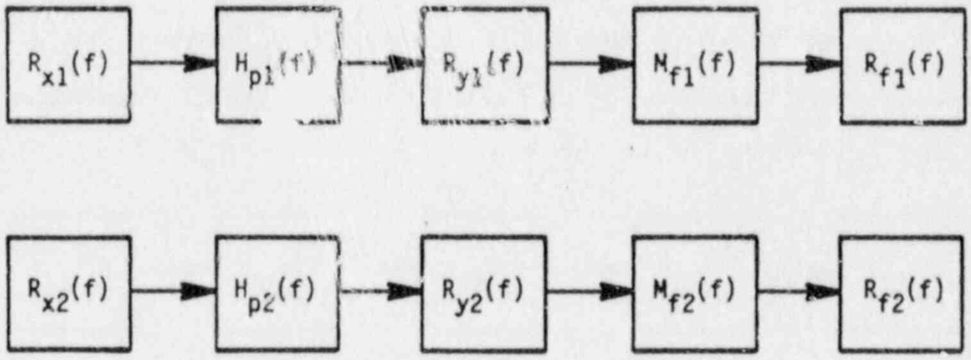
(5) Within the assumptions of mode of failure and critical location, the two items can be defined to be physically similar in a bandwidth up to a composite critical bandwidth Δf_{cc}, where

$$\Delta f_{cc} = (f_{c1} - 1/2\Delta f_{c1}) \text{ to } (f_{c2} + 1/2\Delta f_{c2}). \qquad (3.1)$$

The exact approach by which the above steps are performed will vary significantly depending on the kind of data available, and the nature of the two equipment items. Furthermore, the process must be repeated if more than one mode of failure is suspected to be present, unless all critical bandwidths Δf_{ci} are shown to be included in the composite bandwidth Δf_{cc}. Note also that the magnitudes of the critical transfer functions $H_{pi}(f_i)$ are influenced both by equipment damping and modal participation factors. Thus, if the equipment is dynamically similar (i.e., stiffness, mass, boundary conditions), then similarity of modal participation is assured. Furthermore, if damping is approximately equal, then physical similarity is assured within a given Δf_{cc} simply by showing that the various f_{ci} fall within that band. The useful part of Δf_{cc} as defined above will depend on how the available excitation energy is distributed in the frequency band that corresponds to Δf_{cc} for the equipment in a given case, as will be shown later.

3.3 Dynamic Response Similarity

When used in combination, excitation and physical system similarity are probably sufficient to address most practical problems that will arise in equipment qualification. However, dynamic response similarity is a concept that may be used to extend the qualification by experience even further. "A physical system response can be described through the same quantities as excitation (e.g., duration, frequency content, amplitude, etc.) or through failure modes of the system." Figure 5 provides a more precise definition of dynamic response similarity. That is, given that similarity of response and malfunction behavior can be established, what further can be concluded about the similarity of the excitation and/or the physical system? The implication is that dynamic response similarity can be used in an inverse approach along with physical similarity to establish excitation similarity, or along with excitation similarity to establish physical similarity. This all follows from the interrelationship of the excitation, physical system, and response characteristics as depicted in Figure 1. The various detailed ways in which this interrelationship can be applied to solve practical problems is still very much under development. Some of these applications follow, herein.



Given two independent experiments,

<u>Response Equality:</u>

If $R_{y1}(f) = R_{y2}(f)$ and $R_{f1}(f) = R_{f2}(f)$

along with

Method: A) $H_{p1}(f) = H_{p2}(f)$ and $M_{f1}(f) = M_{f2}(f)$ then $R_{x1}(f) = R_{x2}(f)$

or B) $R_{x1}(f) = R_{x2}(f)$ then $H_{p1}(f) = H_{p2}(f)$ and $M_{f1}(f) = M_{f2}(f)$

so that

$$R_{F1}(f) \equiv R_{F2}(f) \quad \text{for all } f$$

<u>Response Similarity</u>

If $R_{y1}(\Delta f) \approx R_{y2}(\Delta f)$ and $R_{f1}(\Delta f) \approx R_{f2}(\Delta f)$

along with

Method: A) $H_{p1}(\Delta f) \approx H_{p2}(\Delta f)$ and $M_{f1}(\Delta f) \approx M_{f2}(\Delta f)$ then $R_{x1}(\Delta f) \approx R_{x2}(\Delta f)$

or B) $R_{x1}(\Delta f) \approx R_{x2}(\Delta f)$ then $H_{p1}(\Delta f) \approx H_{p2}(\Delta f)$ and $M_{f1}(\Delta f) \approx M_{f2}(\Delta f)$

with Δf_{c1} and Δf_{c2} both contained in Δf_{cc}

so that

$$R_{F1}(\Delta f_{cc}) \approx R_{F2}(\Delta f_{cc}) \quad \text{for given } \Delta f_{cc}$$

where

Δf_{cc} = Preselected composite critical frequency bandwidth

Figure 5. Definition of response similarity.

4. SIMILARITY APPLICATIONS

There are many conceivable practical qualification scenarios to which the previously developed principles may be applied. Within this section, several typical hypothetical scenarios will be described, and details given for use of the principles for providing a solution to a typical problem. Examples which include data taken from actual qualifications will follow in Section 7.0.

4.1 Composite Spectra

Generation of composite spectra is one of the most fundamental requirements for equipment qualification by similarity. One typical objective may be to extend the qualification of a single previously-qualified item. Another typical objective may be to develop a generic data base for use in qualifying other equipment (candidate items) whose physical similarity can be established relative to previously-qualified equipment (reference items), whose available data are used to generate the composite spectrum. In accordance with Reference [2], a composite spectrum is defined to be formed within the envelope of several reference spectra (i.e., TRSs for several reference equipment items), and is likely to produce equal or less response than any one of the individual reference spectra. The procedure for generating the composite must include consideration of all equipment vibrational modes which are significant in determining its structural integrity and functional operability. This section contains several scenarios which include generation of a composite spectrum.

4.1.1 Composite Spectrum for Physically Identical Equipment

For simplicity, a composite spectrum will first be developed for a case which involves only a single item of equipment. Generation of a composite spectrum will be described by the example shown in Figure 6. That is, given a single equipment item that has been qualified to $R_{x1}(f)$ and also to $R_{x2}(f)$, demonstrate that it is also qualified to the composite spectrum $R_{x3}(f)$. This requires the following steps:

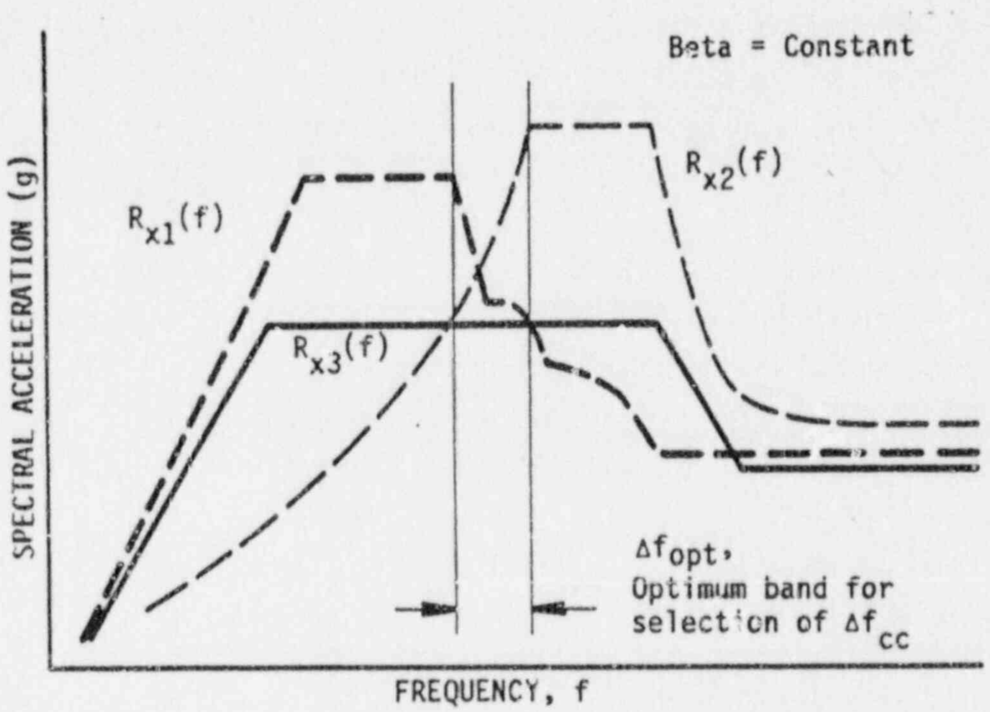


Figure 6. Development of composite response spectrum for physically identical equipment.

(1) Establish the critical transfer function $H_p(f)$ for the item as performed in Paragraph 3.2.2. In this case, physical equality exists since only a single item is involved. The critical frequency range Δf_{cc} is taken as the bandwidth of $H_p(f)$ at 0.7 times the peak value, or $2\zeta_c f_{ci}$ (i.e., $\Delta f_{ci} = \Delta f_{cc}$).

(2) Satisfy excitation similarity by confirming that $R_{x3}(f)$ is equal to or less than both $R_{x1}(f)$ and $R_{x2}(f)$ within Δf_{cc}. By this requirement, the approach is conservative within the critical bandwidth.

(3) Confirm that the ZPA for $R_{x3}(f)$ is equal to or less than the largest ZPA present. By this requirement, the approach is conservative for rigid body response.

(4) Satisfy waveform similarity by confirming that the ZPA/RMS ratio or the maximum spectral amplification factor for the composite spectrum is within the range of those for the individual constituent spectra.

(5) If the absence of multimode interaction cannot be justified (i.e., when the constituent spectra represent sinewave, sinebeat, or other narrowband waveforms), the composite spectrum must be multiplied by 0.7 [7].

It should be noted that the complete determination of the critical bandwidth Δf_{cc} is accomplished in Step 1. However, the utility of the final process is greatly influenced by how the thereby determined Δf_{cc} matches with Δf_{opt}, the "optimum band for selection of Δf_{cc}", as indicated in Figure 6. This has implications on how a data base can optimally be developed from various response spectra that may be available from previous qualifications. Furthermore, if the individual constituent spectra $R_{x1}(f)$ and $R_{x2}(f)$ are based on relatively broadband waveforms, then use of the 0.7 factor is not warranted. Evidence for what constitutes sufficiently broadband waveforms will be developed in Paragraph 4.4.

4.1.2 Composite Spectrum for Physically Similar Equipment (Direct Method)

Consider now development of a composite spectrum $R_{x3}(f)$ for a case where one reference item has been qualified to $R_{x1}(f)$ and a second reference item has been qualified to $R_{x2}(f)$, where the three spectra are as given in Figure 6. Physical similarity for the two reference items will be established by means of Paragraph 3.2.2, which involves direct consideration of equipment dynamic characteristics.

(1) The critical transfer function $H_{pi}(f)$ for each item must be established by the 5-step physically similar process described in Paragraph 3.2.2. For illustration, assume that they correspond to $H_{p1}(f)$ and $H_{p2}(f)$, respectively, in Figure 4. Establish the composite critical bandwidth Δf_{cc} by use of Equation (3.1), which results in the bandwidth Δf_{cc} (1,2) in Figure 4. Thus, physical similarity exists within Δf_{cc} (1,2).

(2) From this point, Steps 2-5 of Paragraph 4.1.1 for physically identical items are also required to generate the composite spectrum for this case.

Note that in view of Step 2 of Paragraph 4.1.1, knowledge about variation in the peak magnitudes on the transfer functions (i.e., Step 4 of Paragraph 3.2.2) is not necessary for generating the composite spectrum. However, use of this step will be necessary for further use of the composite spectrum for qualifying other candidate similar equipment. Furthermore, the comments at the end of Paragraph 4.1.1 which relate to Δf_{opt} as the "optimum bandwidth for selection of Δf_{cc} are again very pertinent.

4.1.3 Composite Spectrum for Physically Similar Equipment (Response Method)

Again, consider the case where one equipment item has been qualified to $R_{x1}(f)$ and a second equipment item has been qualified to $R_{x2}(f)$, where the two spectra are as given in Figure 6. No detailed resonance search data were acquired at elevated response locations on the primary structure during the original qualifications. However, elevated response spectra $R_{y1}(f)$ and $R_{y2}(f)$ were acquired, for it was anticipated that secondary devices might be exchanged on the primary structure at a later date. Generation of a composite response spectrum $R_{x3}(f)$ is now desired. As before, generation of a composite spectrum requires demonstration of physical similarity and excitation similarity. However, in this case, physical similarity must be demonstrated indirectly via response similarity as described in Paragraph 3.3 and Method B in Figure 5, because of the type of data available.

(1) The respective elevated locations on the primary structures at which $R_{y1}(f)$ and $R_{y2}(f)$ were acquired are judged to be critical response locations. Therefore, the elevated spectra become critical response spectra in the dominant critical bandwidths which correspond to resonances of the equipment. It is also noted that, for these bands,

$$R_{y1}(\Delta f_{c1}) \approx R_{y2}(\Delta f_{c2})$$

where the Δf_{ci} are selected at 0.7 times the amplified peak over the ZPA level of the spectrum.

(2) Since both items functioned properly during their previous qualification, by definition:

$$R_{f1}(\Delta f_{c1}) \approx R_{f2}(\Delta f_{c2})$$

for the given excitations $R_{x1}(f)$ and $R_{x2}(f)$.

(3) A critical bandwidth Δf_{cc} is selected so that:

$$R_{x1}(\Delta f_{cc}) \approx R_{x2}(\Delta f_{cc})$$

with both $R_{x1}(\Delta f_{cc})$ and $R_{x2}(\Delta f_{cc})$ greater than $R_{x3}(\Delta f_{cc})$. Thus, excitation similarity is assured, and physical similarity follows within Δf_{cc} indirectly from Method B of Figure 5.

(4) From this point, Steps 3-5 of Paragraph 4.1.1 are again required.

Note that again Step 4 of Paragraph 3.2.2 is not employed for generating the composite spectrum. However, that step is necessary for subsequent use of the composite spectrum for qualifying other candidate similar equipment. In all three examples (4.1.1, 4.1.2, and 4.1.3), the qualification data has been considered as a lower bound for the respective fragility response spectra. Furthermore, the latter two examples represent a procedure whereby a reference data base for a similar set of equipment and its associated composite spectrum can be generated. In both cases, an optimum selection for the reference equipment and associated spectra will be possible, depending on the relationship of the Δf_{cc} developed from the critical transfer functions and the distribution of frequencies in the response spectra.

4.2 Qualification by Similarity

Assume that similarity for a group of existing reference equipment has been established according to Paragraph 3.2.2 and a composite spectrum based on test data for this equipment has been generated according to Paragraph 4.1.2 or 4.1.3. To qualify an additional candidate item for which no previous qualification has been performed, it must be shown that Δf_{ci} for the candidate items falls within Δf_{cc} for the data base items (and, therefore, within Δf_{opt} for the data base excitation spectra). The procedure is as follows:

(1) Establish physical similarity between the candidate item and at least one reference item according to Paragraph 3.2.2.

(2) Note that Step 4 in Paragraph 3.2.2 is satisfied providing that the peak transfer function magnitude for the candidate item is less than or equal to that for at least one reference item in the data base, and the composite spectrum is relatively flat within Δf_{cc}. Magnitudes can be shown by measurements or by similarity of modal participation and damping. Furthermore, the

critical bandwidth Δf_{ci} for the candidate item must fall within the composite critical bandwidth Δf_{cc} for the group of reference equipment.

(3) Qualification of the candidate item to the composite spectrum for the group of reference equipment is therefore accomplished.

4.3 Spectrum Extension

In the past, enveloping of a RRS by a TRS has been an absolute requirement in all qualification scenarios [2], to assure the presence of conservatism. However, the concepts presented herein indicate that absolute enveloping is necessary only within the critical frequency band Δf_{ci} for an equipment item, providing that this band can be established. At the same time, some bounds must be placed on the amount of nonenveloping outside the critical frequency band. This leads to the concept of spectrum extension, which can be used effectively in some practical qualification scenarios. An extended spectrum is one which produces equal or less response than another spectrum that it does not completely envelope.

4.3.1 Qualification Extension for Physically Identical Equipment

Consider first the possibility of extending the validity of qualification for an item for one specified spectrum to other different spectra. For example, in Figure 7, given that an equipment item has been qualified to $R_{x1}(f)$, can the qualification be extended to $R_{x2}(f)$ and/or $R_{x3}(f)$? This requires the following steps, which are based on the previous concepts and further development initially published in Reference [8].

(1) Establish the critical frequency response function $H_p(f)$ for the item by the 5-step physical similarity process in Paragraph 3.2.2. In this case, physical identity exists. The critical frequency range Δf_{cc} is taken as the bandwidth of $H_p(f)$ at 0.7 times the peak value, or $2\zeta_c f_c$.

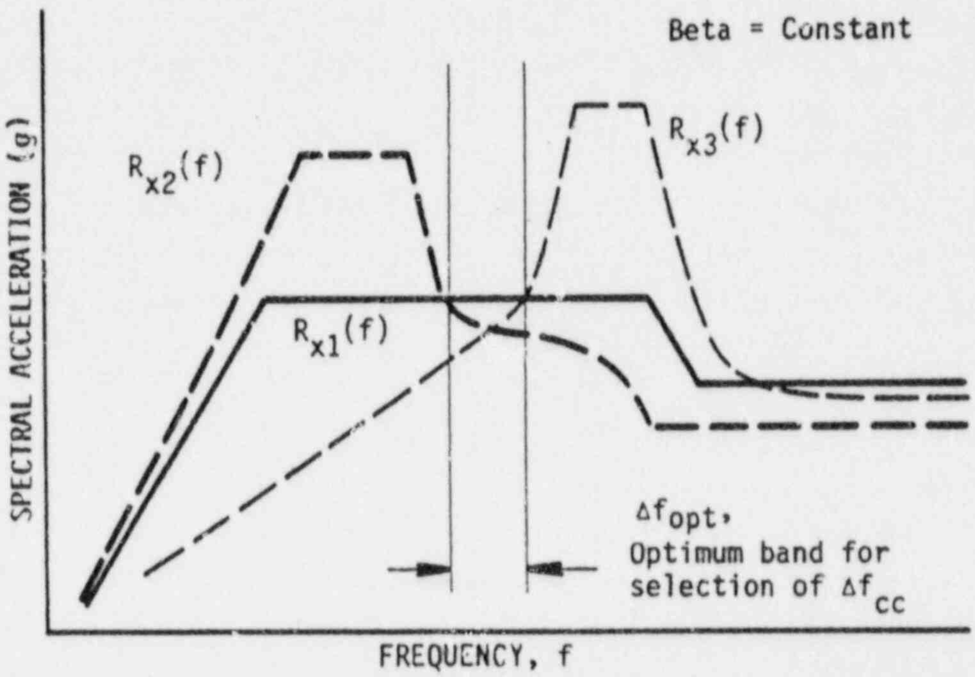


Figure 7. Use of spectrum extension for physically identical equipment.

(2) Note that $R_{x1}(f)$ is equal to or greater than $R_{x2}(f)$ and $R_{x3}(f)$ within Δf_{cc} (see Figure 7).

(3) Confirm that the ZPA for $R_{x1}(f)$ is equal to or greater than that for $R_{x2}(f)$ and $R_{x3}(f)$.

(4) Confirm that the ZPA/RMS ratio or the maximum spectral amplification factor for $R_{x2}(f)$ and $R_{x3}(f)$ is approximately equal to that for $R_{x1}(f)$.

(5) Confirm that $R_{x2}(f)$ or $R_{x3}(f)$ does not exceed $R_{x1}(f)$ X $A\, R_p(f)$ where $A\, R_p(f)$ is the normalized narrowband fragility function obtained from the critical transfer function by

$$A\, R_p(f) = \frac{1}{2\zeta_{ci}} H_p^{-1}(f) \qquad (4.1)$$

and the constant "A" is chosen to make the minimum value of $A\, R_p(f)$ equal to 1.0. Example plots for $R_{x1}(f)$ and $A\, R_p(f)$ are shown in Figure 8. Note that for this plot, $R_{x1}(f)$ should be calculated at the same damping ratio as that of the equipment, i.e., $\beta = \zeta_c$.

Equation (4.1) represents the frequency sensitivity of the equipment item in terms of a narrowband (sinewave input) fragility response spectrum. Thus, it gives some quantitative indication of the extremes to which the excitation spectrum $R_{x1}(f)$ can be extended outside the critical frequency band

$$\Delta f_{ci} = 2\zeta_{ci} f_{ci}$$

This requirement is necessary, but not sufficient to assure qualification to the extended spectrum. A bound on the RMS value must also be included, which is assured by Steps 3 and 4 above.

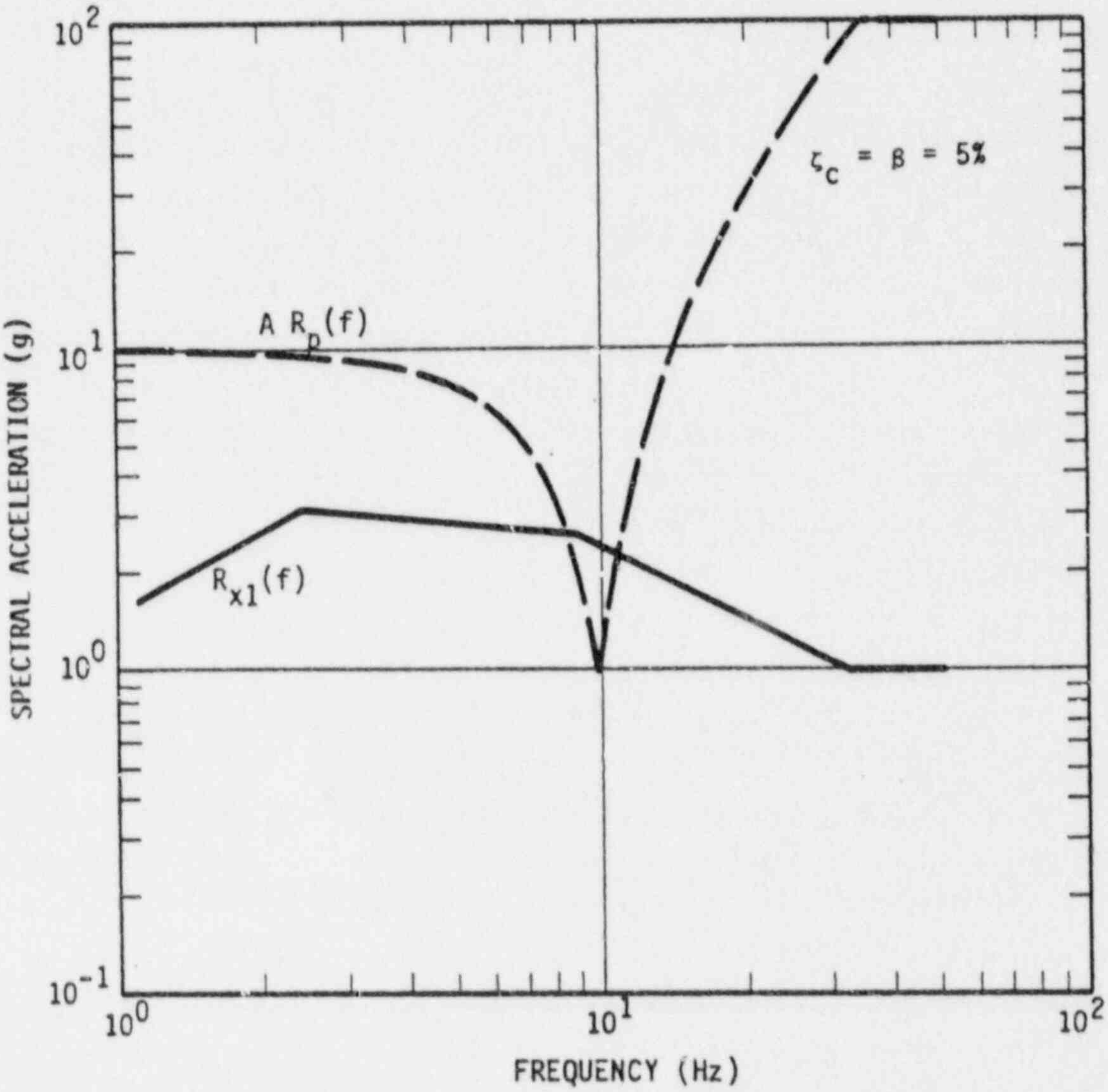


Figure 8. Component functions for development of an extended spectrum.

The equipment item is, therefore, qualified to any extended spectrum that satisfies the above requirements. This procedure is especially useful to demonstrate that qualification is satisfied for an actual earthquake event whose spectrum is $R_{x2}(f)$, which occurs after the item had been qualified to $R_{x1}(f)$.

4.3.2 Qualification Extension For Physically Similar Equipment

Consider now the case where $R_{x1}(f)$ in Figure 7 represents a composite spectrum that has been generated for physically similar items as described in Paragraph 4.1.2. The 5-step process described in Paragraph 4.3.1 can now be applied to extend the qualification of the entire set of equipment. However, in this case, note that in carrying out Step 5, the normalized fragility function A $R_{pi}(f)$ for each item of the data base must be considered. The lower envelope of these functions would be appropriate for use for the entire set. Such a procedure is somewhat analogous to the inverse of generating a composite response spectrum.

4.4 Application to Simple Primary/Secondary Systems

Application and validity of the previously-described principles will be demonstrated by means of a hypothetical support-excited two degree of freedom, damped oscillator system. The support is excited by some prescribed motion which is transferred to the first damped oscillator of natural frequency f_1 and mass M_1, and then to the second damped oscillator of natural frequency f_2 and M_2. Both oscillators are assumed to have a damping coefficient of $\beta = 0.05$. Such a system was used in Reference [7] for demonstrating effects of modal interaction on fragility data. If $M_1 = 1000$ lb and $M_2 = 100$ lb, the system approximately represents a secondary component (transformer) supported on a primary structure (cabinet or rack). If $M_1 = 1000$ lb and $M_2 = 10$ lb, the system approximately represents a lightweight secondary device (relay) supported on a primary structure (cabinet).

In order to demonstrate the principles, the three typical spectra shown in Figure 9 will be utilized. $R_{x1}(f)$ contains relatively low

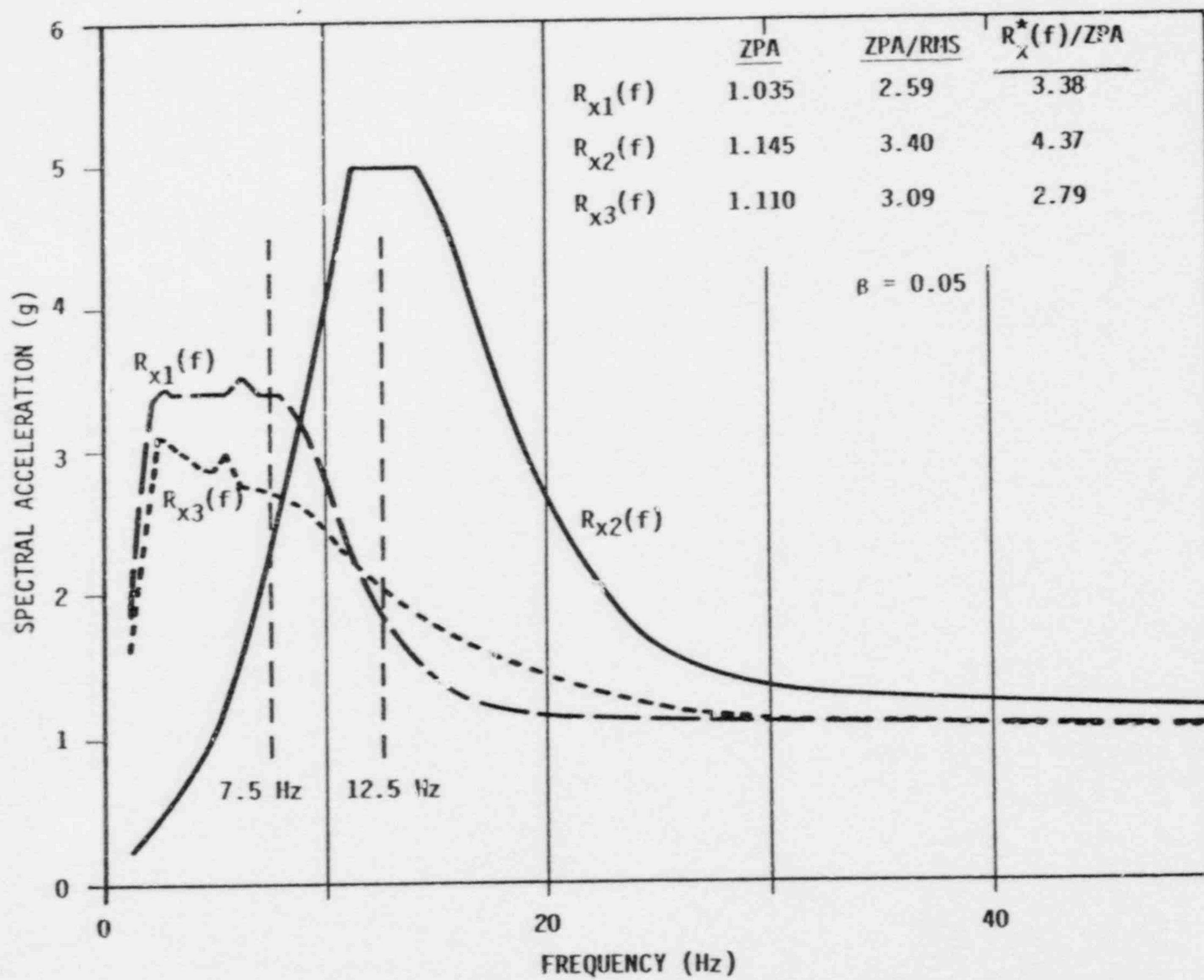


Figure 9. Development of composite spectra or extended spectra.

frequencies, $R_{x2}(f)$ high frequencies, and $R_{x3}(f)$ rather broadband frequencies. The latter spectrum is based on R.G. 1.60. For each spectrum, an acceleration excitation time history was developed, and applied to the support for the simple primary/secondary system. Each time history was synthesized so that its ZPA/RMS ratio was nearly 3.0 for its strong motion. This ratio, as well as the maximum spectral amplification factor, is given for each of the spectra in Figure 9. The system was assumed to include various mass and natural frequency combinations, and the peak acceleration response at each of the two masses was calculated for each of the three acceleration excitations. Results are tabulated in Table 1a for M_1 = 1000 lb and M_2 = 100 lb, and five natural frequency combinations. Further results are tabulated in Table 1b for M_1 = 1000 lb and M_2 = 10 lb, and five natural frequency combinations. Furthermore, the transfer functions for the former mass ratio and each of the five frequency combinations are shown in Figures 10a-e, while similar data are shown for the latter mass ratio in Figures 11a-e. In these plots, $H_p(f)$ denotes a primary structure critical transfer function, while $H_s(f)$ denotes a secondary structure critical transfer function. Only $H_p(f)$ will be used directly in the examples. Furthermore, resonances indicated by these transfer functions do not exactly coincide with the indicated natural frequencies f_1 and f_2, since the latter represent uncoupled, undamped frequencies for the respective individual oscillator. Various parts of these data will now be used to demonstrate application and verification of the previous principles. At the same time, results are sought which indicate how spectral bandwidth influences whether a 0.7 modal interaction factor should be applied. In all cases, the criteria for qualification will be values for peak acceleration response at Mass 1 or Mass 2.

4.4.1 Composite Spectrum

Example 1 - Identical Equipment

Consider $H_p(f)$ of Figure 10a as the critical transfer function that was measured for an equipment item that is assumed to be subject to peak acceleration failure. It has been qualified to $R_{x1}(f)$ and $R_{x2}(f)$ in

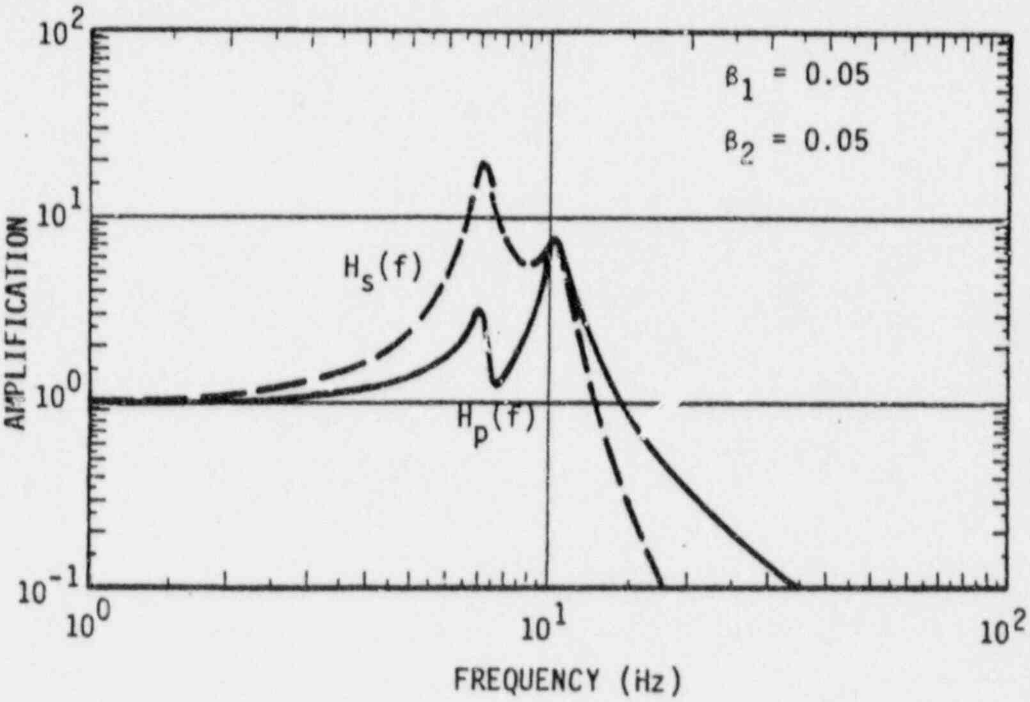
TABLE 1. PEAK-g ACCELERATION RESPONSES FOR SIMPLE PRIMARY/SECONDARY SYSTEM

Table 1a. M_1 = 1000 lb, M_2 = 100 lb, $\beta_1 = \beta_2 = 0.05$

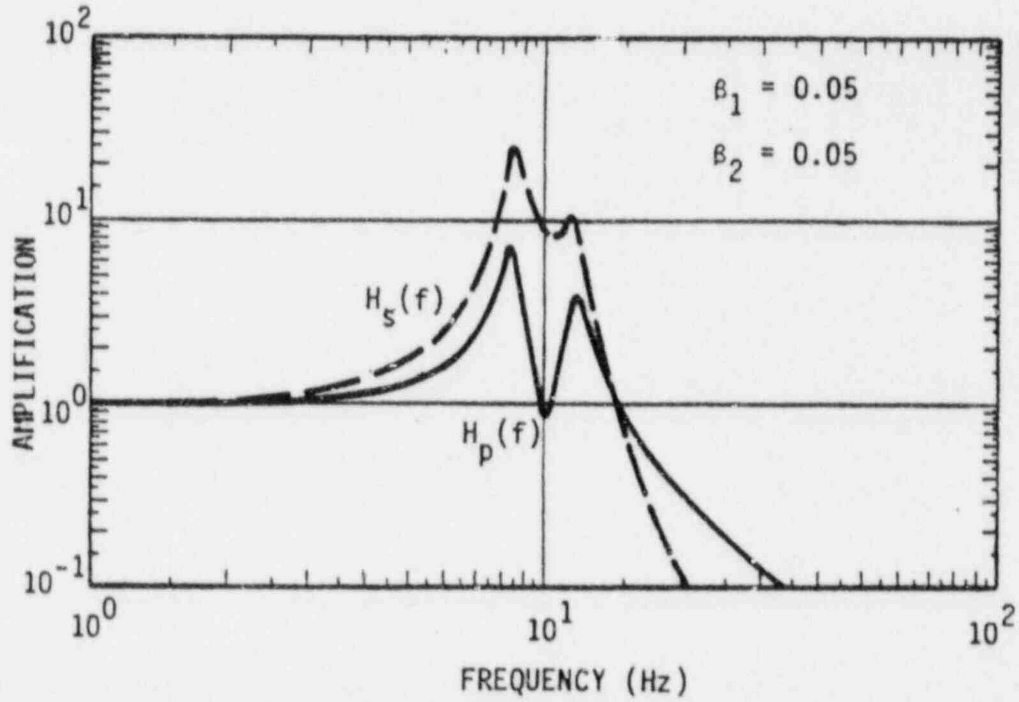
	$f_1 = 10$ $f_2 = 7.5$	$f_1 = 10$ $f_2 = 10$	$f_1 = 10$ $f_2 = 12.5$	$f_1 = 7.5$ $f_2 = 10$	$f_1 = 12.5$ $f_2 = 10$
$R_{x1}(f)$	1.035	1.035	1.035	1.035	1.035
M_1	2.016	2.362	3.096	3.098	2.035
M_2	6.759	7.435	5.989	5.627	5.661
$R_{x2}(f)$	1.145	1.145	1.145	1.145	1.145
M_1	3.200	2.817	3.231	1.737	4.102
M_2	4.895	9.656	8.587	4.317	10.049
$R_{x3}(f)$	1.110	1.110	1.110	1.110	1.110
M_1	1.916	1.997	2.547	2.427	1.685
M_2	4.932	5.270	4.236	4.513	4.599

Table 1b. M_1 = 1000 lb, M_2 = 10 lb, $\beta_1 = \beta_2 = 0.05$

	$f_1 = 10$ $f_2 = 7.5$	$f_1 = 10$ $f_2 = 10$	$f_1 = 10$ $f_2 = 12.5$	$f_1 = 7.5$ $f_2 = 10$	$f_1 = 12.5$ $f_2 = 10$
$R_{x1}(f)$	1.035	1.035	1.035	1.035	1.035
M_1	2.628	2.697	2.811	3.626	1.880
M_2	7.874	9.882	4.760	7.817	4.685
$R_{x2}(f)$	1.145	1.145	1.145	1.145	1.145
M_1	3.946	3.311	3.936	2.156	5.012
M_2	6.306	22.139	11.812	6.161	12.185
$R_{x3}(f)$	1.110	1.110	1.110	1.110	1.110
M_1	2.295	2.242	2.421	2.773	1.957
M_2	5.838	10.506	5.404	5.566	5.475

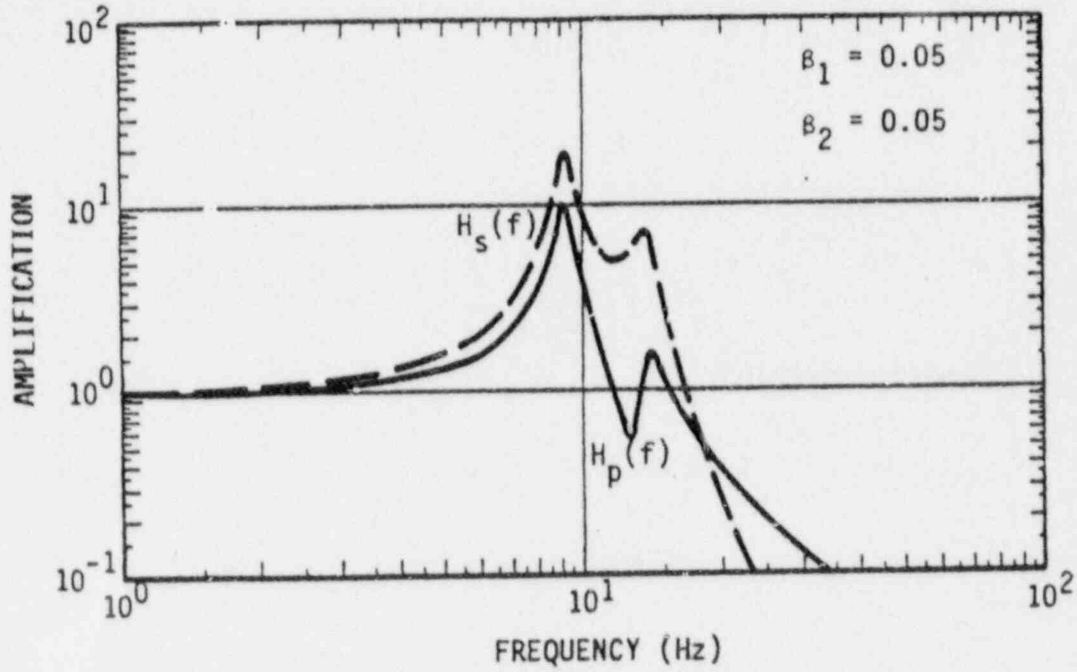


a. f_1 = 10 Hz, f_2 = 7.5 Hz

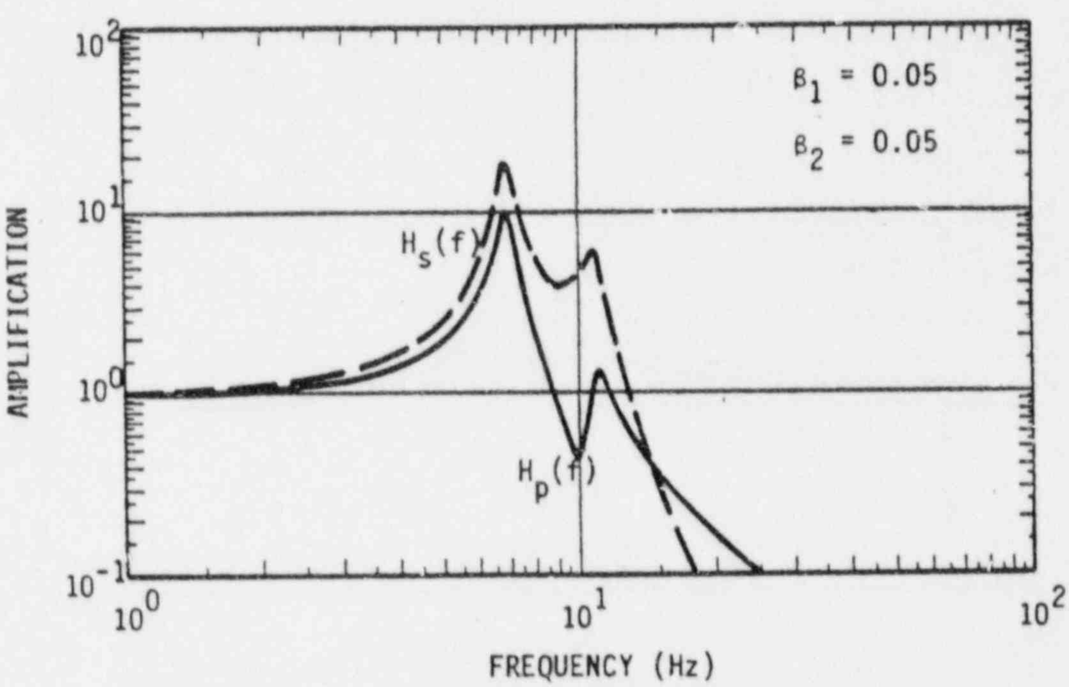


b. f_1 = 10 Hz, f_2 = 10 Hz

Figure 10. Transfer functions for M_1=1000 lb, M_2=100 lb.

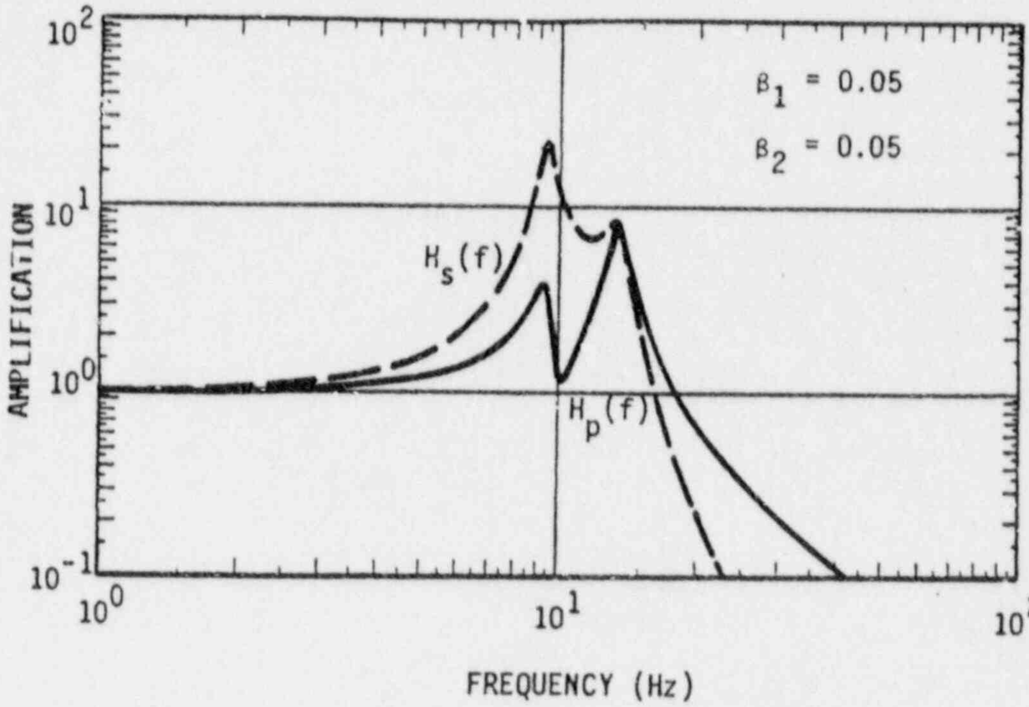


c. f_1 = 10 Hz, f_2 = 12.5 Hz



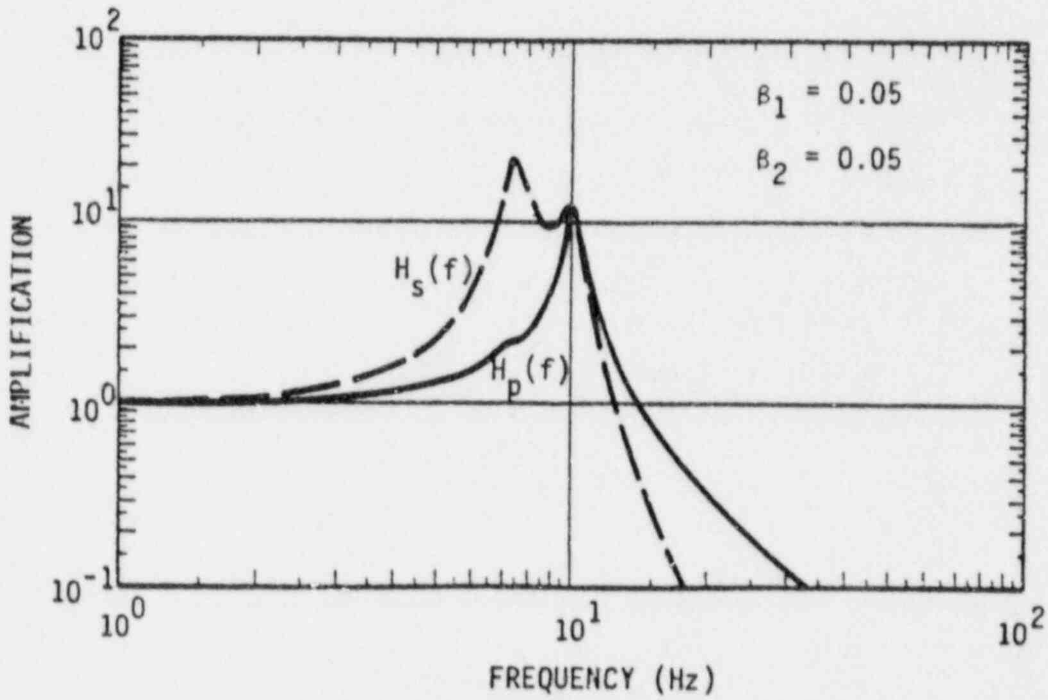
d. f_1 = 7.5 Hz, f_2 = 10 Hz

Figure 10. Transfer functions for M_1=1000 lb, M_2=100 lb.



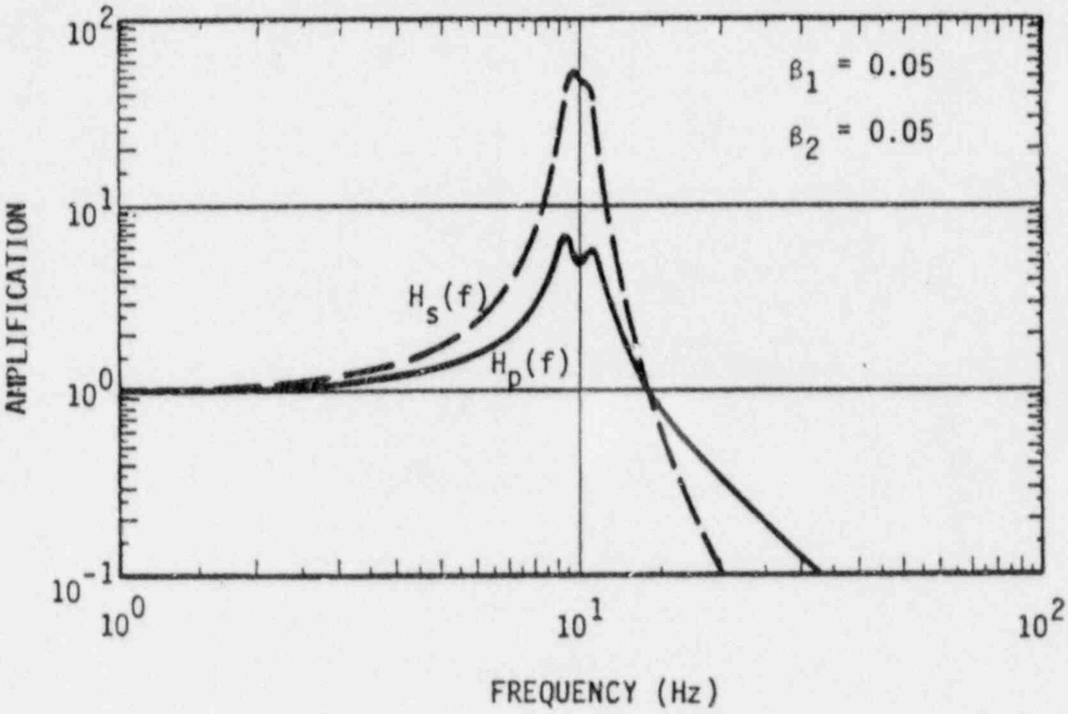
e. f_1 = 12.5 Hz, f_2 = 10 Hz

Figure 10. Transfer functions for M_1=1000 lb, M_2=100 lb.

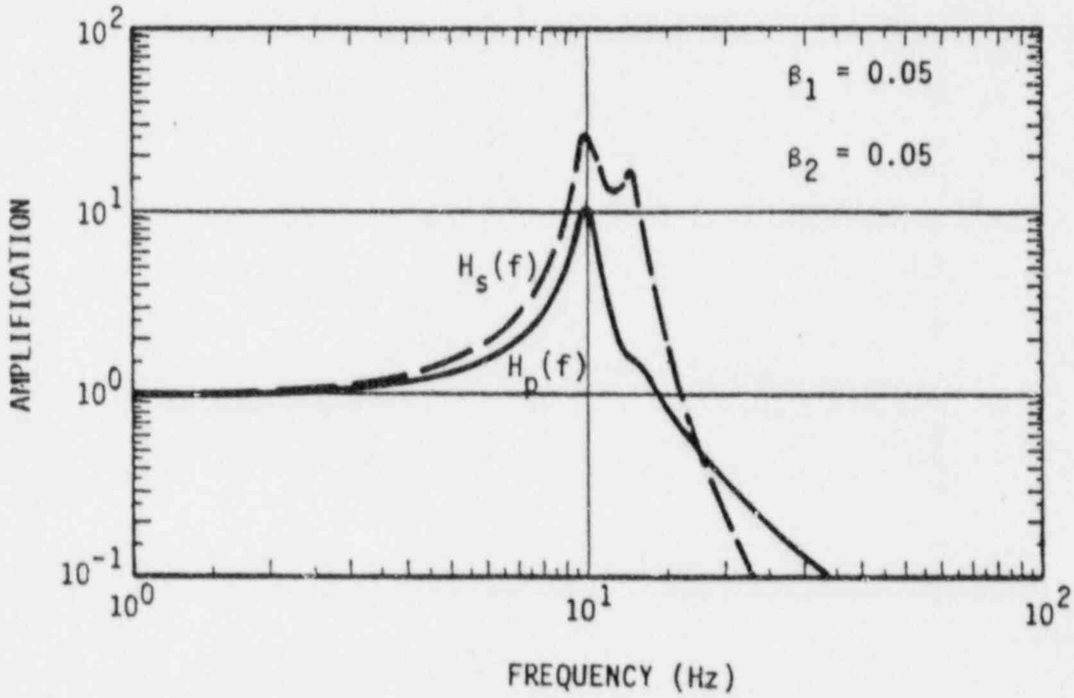


a. f_1 = 10 Hz, f_2 = 7.5 Hz

Figure 11. Transfer functions for M_1=1000 lb, M_2=10 lb.

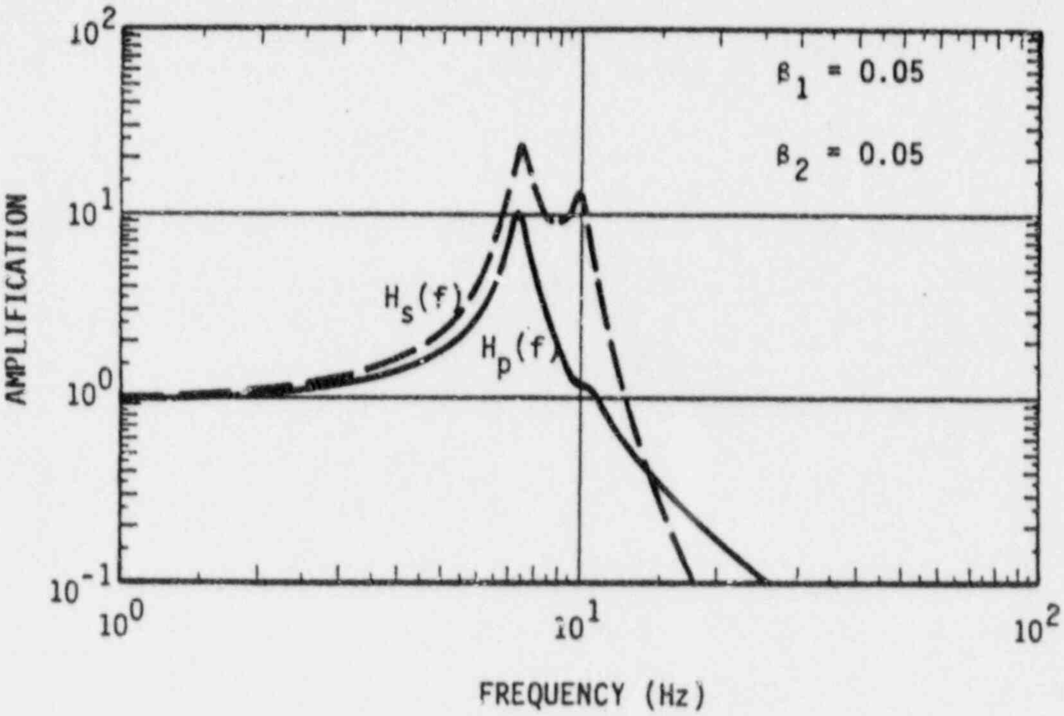


b. f_1 = 10 Hz, f_2 = 10 Hz

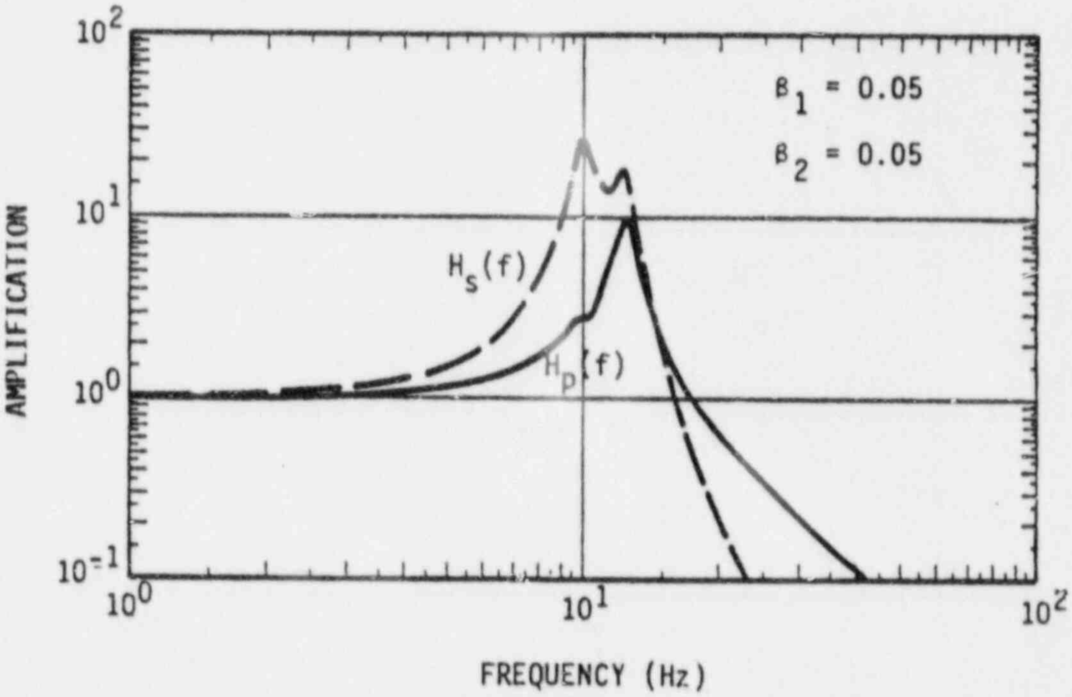


c. f_1 = 10 Hz, f_2 = 12.5 Hz

Figure 11. Transfer functions for M_1=1000 lb, M_2=10 lb.



d. f_1 = 7.5 Hz, f_2 = 10 Hz



e. f_1 = 12.5 Hz, f_2 = 10 Hz

Figure 11. Transfer functions for M_1=1000 lb, M_2=10 lb.

Figure 9, and its qualification to $R_{x3}(f)$ is to be determined. This is an application of Paragraph 4.1.1. For this case from Figure 10a, $\Delta f_{ci} = \Delta f_{cc}$ and is about 1 Hz bandwidth centered at about 10.5 Hz (although two peaks are present, the dominant one is selected). By referring to Figure 9, the maximum spectral amplification factors are all similar (i.e., compared to 7.5 and 10.0, respectively, for a sinebeat or a sinewave). Thus, Steps 1-4 of Paragraph 4.1.1 are all satisfied and, if Step 5 is applied to $R_{x3}(f)$, the procedure asserts that the item is also qualified to at least 0.7 $R_{x3}(f)$. This assertion can be verified by referring to Table 1a. Mass M_1 has already been subject to 2.016 g by $R_{x1}(f)$ and 3.200 g by $R_{x2}(f)$. It is subject to 1.916 g by $R_{x3}(f)$. Mass 2 is subject to 6.759 g by $R_{x1}(f)$, 4.895 g by $R_{x2}(f)$, and 4.932 g by $R_{x3}(f)$. Thus, each mass very nearly has been subject to more acceleration by <u>both</u> of the original spectra than is demanded by $R_{x3}(f)$. Therefore, the assertion that the equipment is qualified to the composite $R_{x3}(f)$ is verified, even if the 0.7 factor of Step 5 is not applied. This result appears to indicate that $R_{x1}(f)$ and $R_{x2}(f)$ are sufficiently broadband for this case so that no modal interaction correction is necessary.

This example can be applied by assuming $H_p(f)$ to be any one of the primary transfer functions from Figures 10a-e, and using the corresponding peak acceleration data from Table 1a. It will be found that all equipment items, except for that in Figure 10d, are qualified to $R_{x3}(f)$, even though Step 2 of Paragraph 4.1.1 is not quite satisfied in some cases and Step 5 is not applied (i.e., some conservatism appears to be present in the procedure for these cases). The 0.7 reduction factor of Step 5 must be applied to the Figure 10d item for the procedure to produce a valid qualification. However, it is suspected that significant violation of Step 2 is the major reason for difficulty with this case, rather than narrowness of the spectra.

Now consider Example 1 to be applied similarly to the set of equipment whose results are indicated in Figure 11 (i.e., M_1 = 1000 lb, M_2 = 10 lb). By referring to Table 1b, it is found that for equipment whose critical transfer function is represented by $H_p(f)$ in Figure 11a, peak accelerations for both M_1 and M_2 are less for $R_{x3}(f)$ (i.e., 2.295 g and 5.838 g) than they are for both $R_{x1}(f)$ (i.e., 2.628 g and 7.874 g) and $R_{x2}(f)$ (i.e., 3.946 g and 6.306 g) Thus, for this case, qualification to $R_{x3}(f)$ is assured without applying any reduction factor for modal interaction. However, if the equipment is to be represented by any of Figures 11b-e, it will be found that a reduction factor of 0.7 must be applied to make qualification of all cases valid. By comparing the critical bandwidth Δf_{cc} for items represented by Figures 11b and 11c and the optimum bandwidths in Figure 9 (i.e., 8 Hz to 11.5 Hz), it appears that Step 2 of Paragraph 4.1.1 has been satisfied, so that genuine modal interaction necessitates use of the 0.7 factor. However, a similar comparison for items represented by Figures 11d and 11e show that Step 2 is violated, which probably is the major reason for a reduction factor to be necessary.

Example 2 - Similar Equipment

Consider that $H_{p1}(f)$ of Figure 10a is the critical transfer function that was measured for an equipment Item 1 that has been qualified to $R_{x1}(f)$. Consider further that $H_{p2}(f)$ of Figure 10c is the critical transfer function that was measured for an equipment Item 2 that has been qualified to $R_{x2}(f)$. Qualification of both items to a composite spectrum $R_{x3}(f)$ is now to be determined. This is an application of Paragraph 4.1.2. For Item 1, Δf_{c1} is a 1 Hz bandwidth centered at about 10.5 Hz. For Item 2, Δf_{c2} is about 1 Hz bandwidth centered at about 9 Hz. Thus, Δf_{cc} extends from 8.5 to 11.0 Hz. The procedure now asserts that both items are qualified to at least 0.7 $R_{x3}(f)$. This assertion is checked by referring to Table 1a, Columns 1 and 3, where it can be seen that both masses of both items are subject to less peak acceleration by $R_{x3}(f)$ directly than by their respective initial spectra (except where only a slight difference exists for M_2 of Item 1, i.e., 4.932 g > 4.895 g). Thus, the assertion is very nearly true, even though the 0.7 factor is not applied, and is definitely true when this factor is applied. It appears that bandwidths of the spectra are not an issue in this case either. Note that valid qualification requires that both masses be subject to less peak acceleration by 0.7 $R_{x3}(f)$ than by both $R_{x1}(f)$ and $R_{x2}(f)$, and this must be true in each equipment item.

Example 2 may also be applied to the equipment represented by Figure 11a [Item 1 qualified to $R_{x1}(f)$] and Figure 11c [Item 2 qualified to $R_{x2}(f)$]. Qualification of both items to $R_{x3}(f)$ is sought, where Δf_{cc} now is a bandwidth of about 1 Hz, centered near 10 Hz. The procedure asserts that qualification to at least $R_{x3}(f)$ is assured. To verify, consult Table 1b, Columns 1 and 3, where the peak accelerations are listed. For a valid qualification, accelerations corresponding to 0.7 $R_{x3}(f)$ must be less than those for both $R_{x1}(f)$ and $R_{x2}(f)$ for both respective masses in each equipment item. It is seen that $R_{x3}(f)$ must be reduced to provide a valid qualification for Item 2 (i.e., 5.404 g > 4.760 g), while no reduction is required for Item 1 (i.e., 2.295 g < 2.628 g, 3.946 g for M_1; while 5.838 g < 7.874 g, 6.306 g for M_2). Hence, qualification to 0.7 $R_{x3}(f)$ is verified. This example demonstrates a case where $R_{x1}(f)$ and $R_{x2}(f)$ are individually too narrow to produce the same modal interaction as the composite spectrum $R_{x3}(f)$ and, therefore, the 0.7 factor must be applied.

4.4.2 Qualification by Similarity

Example 3 - Large Modal Interaction

Consider an equipment item whose critical transfer function is given by Figure 10b, wherein large modal interaction is indicated by the proximity of two modes. Given the composite spectrum $R_{x3}(f)$ of Figure 9 which has been generated by Example 2 of Paragraph 4.4.1, prove that an equipment item, whose $H_{p3}(f)$ is given by Figure 10b, is qualified to 0.7 $R_{x3}(f)$. This is an application of Paragraph 4.2. Note that both peaks of $H_{p3}(f)$ are relatively significant, but also both fall within the established Δf_{cc} of 8.5 to 11.0 Hz. Therefore, according to Paragraph 3.2.2, the effect of both modes can be considered simultaneously. Thus, physical similarity exists within Δf_{cc} and, according to Paragraph 4.2, qualification of Item 3 to 0.7 $R_{x3}(f)$ is assured. For this to be true, first the peak accelerations of both masses for excitation by 0.7 $R_{x3}(f)$ should be equal or less than those for both $R_{x1}(f)$ and $R_{x2}(f)$, when each excitation is applied to Item 3. Note from Table 1a, Column 2, that for M_1, 0.7 (1.997) g is less than 2.362 g or 2.817 g; for M_2, 0.7 (5.276) g is less than 7.435 g or 9.656 g). Second, the response to 0.7 $R_{x3}(f)$ for both masses of Item 3 should be less than those of the respective masses for Items 1 and 2, when subject to $R_{x1}(f)$ and $R_{x2}(f)$. Note that for Mass 1, 0.7 (1.997) for Item 3 (Column 2) is less than 2.016 g or 3.200 g for Item 1 (Column 1) and 3.096 g or 3.231 g for Item 2 (Column 3). Furthermore, for Mass 2, 0.7 (5.270) for Item 3 (Column 2) is less than 6.759 g or 4.895 g for Item 1 (Column 1) and 5.989 g or 8.587 g for Item 2 (Column 3). Note that verification of the qualification for Mass 2 would not be possible without application of the 0.7 factor. This result clearly indicates that it is not always obvious when the 0.7 modal interaction factor can be omitted.

Example 3 may similarly be applied to equipment represented by Figures 11a [Item 1 qualified to $R_{x1}(f)$], Figure 11c [Item 2 qualified to $R_{x2}(f)$], which are used to generate a composite which is 0.7 $R_{x3}(f)$. For Item 1, Δf_{c1} is a 1 Hz bandwidth centered at 10 Hz; while for Item 2, Δf_{c2} is also a 1 Hz bandwidth centered at 10 Hz. Thus, Δf_{cc} extends only from 9.5 to 10.5 Hz. Qualification of Item 3 (Figure 11b) is now sought. It may be noted that $H_{p3}(f)$ in Figure 11c is somewhat wider than Δf_{cc} = 1 Hz, centered about 10 Hz. Therefore, physical similarity does not exist, and it may be suspected that Item 3 will not qualify. By consulting Table 1b, Column 2, it is found that for Mass 1, 0.7 (2.242) g is less than 2.697 g or 3.311 g; but for Mass 2, 0.7 (10.506) g <u>is not</u> less than 6.306 g or 4.760 g. Thus, Item 3 indeed does not qualify to 0.7 $R_{x3}(f)$, since this violates the second condition prescribed in the above paragraph.

<u>Example 4 - Broad Bandwidth</u>

Consider that $H_{p1}(f)$ of Figure 10d is the critical transfer function that has been measured for an equipment Item 1 that has been qualified to

$R_{x1}(f)$. Consider further that H_{p2} of Figure 10e is the critical transfer function that has been measured for an equipment Item 2 that has been qualified to $R_{x2}(f)$. Determine qualification of both items to $R_{x3}(f)$. From the transfer functions $H_{p1}(f)$ and $H_{p2}(f)$, Δf_{cc} extends from about 6.5 to 14.5 Hz, which is a comparatively broad bandwidth. It may be noted from Figure 9 that excitation similarity does not exist throughout this entire range (i.e., Paragraph 4.1.1, Step 2 is not satisfied). Nevertheless, the results in Table 1a indicate that both items are qualified to 0.7 $R_{x3}(f)$, since peak accelerations for both M_1 and M_2 which result from 0.7 $R_{x3}(f)$ are less than their respective values when subject to their initial spectra. (i.e., From Table 1a for Item 1 in Column 4, 0.7 (2.427) g is less than 3.098 g or 1.737 g, and 0.7 (4.513) g is less than 5.627 g or 4.317 g. Furthermore, for Item 2 in Column 5, 0.7 (1.685) g is less than 2.035 g or 4.102 g and 0.7 (4.599) g is less than 5.611 g or 10.049 g.) However, it is again suspected that the 0.7 factor in this case has simply compensated for the violation of physical similarity. In fact, one may further consider other equipment items whose critical transfer functions are given by Figures 10a, b, and c. Peak accelerations for each of the masses are less than those of Item 1, Column 4, and Item 2, Column 5, providing that the composite spectrum is reduced by a 0.7 factor. Thus, use of such a factor appears to allow some stretching of the requirements for similarity. This could be of use when suitable reference data were not available.

Application of Example 4 to items identified by Figure 11 may now be pursued. Consider that $H_{p1}(f)$ of Figure 11d is the critical transfer function for Item 1, qualified to $R_{x1}(f)$. Let $H_{p2}(f)$ of Figure 11e be the critical transfer function for Item 2, qualified to $R_{x2}(f)$. Verify qualification of both items to 0.7 $R_{x3}(f)$. It may be noted that Δf_{cc} extends from about 6.5 to 13.5 Hz. Here, 0.7 $R_{x3}(f)$ is less than the other two spectra throughout this frequency range. By consulting Table 1b, it can be seen that qualification is assured, providing that the 0.7 factor is applied to $R_{x3}(f)$, as indicated. It also appears that other items represented by Figures 11a and 11c also are qualified, providing that the 0.7 reduction factor is applied. Note that an item represented by

Figure 11b does not qualify [i.e., 0.7 (10.506) g is not less than 6.161 g or 4.685 g]. This results from the fact that Δf_{c3} is wider than Δf_{c1} or Δf_{c2}, and physical similarity does not exist.

Most of the above examples indicate that use of the 0.7 modal interaction factor must be considered very carefully when generating composite spectra. It appears that it is applicable not only to spectra which represent sine-dwells or sinebeats, but those which represent narrowband random signals (i.e., significantly filtered floor level motion) as well. The only general statement that appears to be conservative at this point is that the 0.7 factor is not warranted if all constituent spectra are essentially similar to ground level motion.

4.4.3 Spectrum Extension

Example 5 - Identical Equipment

Consider $H_p(f)$ of Figure 10d as the critical transfer function that was measured for an equipment item that has been qualified to $R_{x1}(f)$. Can qualification be extended to $R_{x2}(f)$ and $R_{x3}(f)$? This is an application of Paragraph 4.3.1. Here, Δf_{cc} is about a 1 Hz bandwidth centered at 7.5 Hz. Step 3 of Paragraph 4.3.1 is only approximately satisfied. Step 5 can be confirmed on a point by point basis. Thus, according to the procedure, the equipment is qualified to both $R_{x2}(f)$ and $R_{x3}(f)$. This may be verified by consulting Table 1a. Note that M_1 experienced 3.098 g and M_2 experienced 5.627 g during the initial qualification. The respective peak values for each mass are less for both of the other spectra, so that the assertion is verified.

Now consider $H_p(f)$ of Figure 11d as the critical transfer function that was measured for an equipment item that was qualified to $R_{x1}(f)$. Can qualification be extended to $R_{x2}(f)$ and $R_{x3}(f)$? Here, Δf_{cc} is a 1 Hz bandwidth, centered at 7.0 Hz. By referring to Table 1b, M_1 experienced 7.817 g and M_2 experienced 3.626 g during the initial qualification. The respective peak values for each mass are less for both of the other spectra, so that qualification to them is verified.

Example 6 - Similar Equipment

Consider that the $H_p(f)$ for Figures 10b, 10c, and 10e each represent equipment items that have been qualified to $R_{x2}(f)$. For this case, Δf_{cc} extends from 7.5 to 14.5 Hz. For these similar equipment items, the qualification can be extended to both $R_{x1}(f)$ and $R_{x3}(f)$, according to Paragraph 4.3.2 (even though Step 2 of Paragraph 4.3.2 is violated somewhat for Item 10b). This can be verified by consulting Table 1a, Columns 3 and 5. Note that for each of the three equipment items, both M_1 and M_2 have experienced greater peak accelerations for $R_{x2}(f)$ than they would for $R_{x1}(f)$ and $R_{x3}(f)$. Thus, the assertion is verified. It may be noted that the other two equipment items (10a and 10d) cannot be included, since attempting to extend Δf_{cc} down to 6.5 Hz excessively violates excitation similarity required by Paragraph 4.3.1, Step 2.

To apply this example to a lightweight secondary device on a primary structure, let $H_p(f)$ for Figure 11b, 11c, and 11e each represent items that have been qualified to $R_{x2}(f)$. For this case, Δf_{cc} extends from 8.5 to 13.5 Hz. Can this qualification be extended to $R_{x1}(f)$ and $R_{x3}(f)$? By consulting Table 1b, Columns 2, 3, and 5, it can be seen that both M_1 and M_2 experienced greater peak accelerations for $R_{x2}(f)$ than they would for the other two spectra. Thus, application of the procedure in Paragraph 4.3.2 is verified. Here also, the qualification cannot be extended for items represented by Figures 11a and 11d.

It is apparent from Examples 5 and 6 that Steps 2 and 5 of Paragraph 4.3.1 are most important in determining whether a spectrum extension can successfully be achieved in a given case. These two steps preclude most of the other equipment represented by the transfer functions of Figures 10 or 11 from having spectrum extensions applied with the three spectra as given in Figure 9. However, it is obvious that if these spectra were changed in amplitude, other possibilities would arise. The obvious conclusion is that how the response spectrum energy matches with the critical transfer function peaks is most important.

5. RELATIONSHIP TO PREVIOUSLY PUBLISHED WORK

Some of the earliest impetus for development of qualification by experience data has been published by EPRI/ANCO [9], and has been aimed primarily at qualification of existing equipment in operating plants. Nevertheless, the information is also appropriate for equipment qualification in general, providing that the data is used appropriately. Since these developments preceded the recent standard IEEE 344 [2] as well as the recent corresponding draft standard for mechanical equipment [10], some note of terminology differences is necessary. In particular, the early work refers to generic classes of equipment, and these classes are sometimes subdivided into groups with common degrees of diversity. Herein, we note that generic classes are synonymous with general physical similarity and low diversity is synonymous with high physical similarity, etc. Furthermore, although the method outlined herein for establishing physical similarity was not used per se in Reference [9], we will describe how the two methods are analogous in concept, but differ in the degree of details required.

Table 2 shows a list of equipment (from Reference 9) for generically similar classes which were based on the function/malfunction of the items, dynamic similarity, and geometric similarity. A judgment of similarity was based on parameters of weight, size, manufacturer, operating principle, etc. (We may add at this point that some example checklists for evaluating physical similarity by judgment also are given in the Appendix to Reference [10].) Thus, although the details of the selection of the equipment classes is not given in the EPRI/ANCO report, it would appear that the method for establishing physical similarity outlined in Paragraph 3.2 in effect was employed. However, critical frequencies and bandwidths, modal participation, and damping characteristics were established from physical properties, rather than from documented transfer function data.

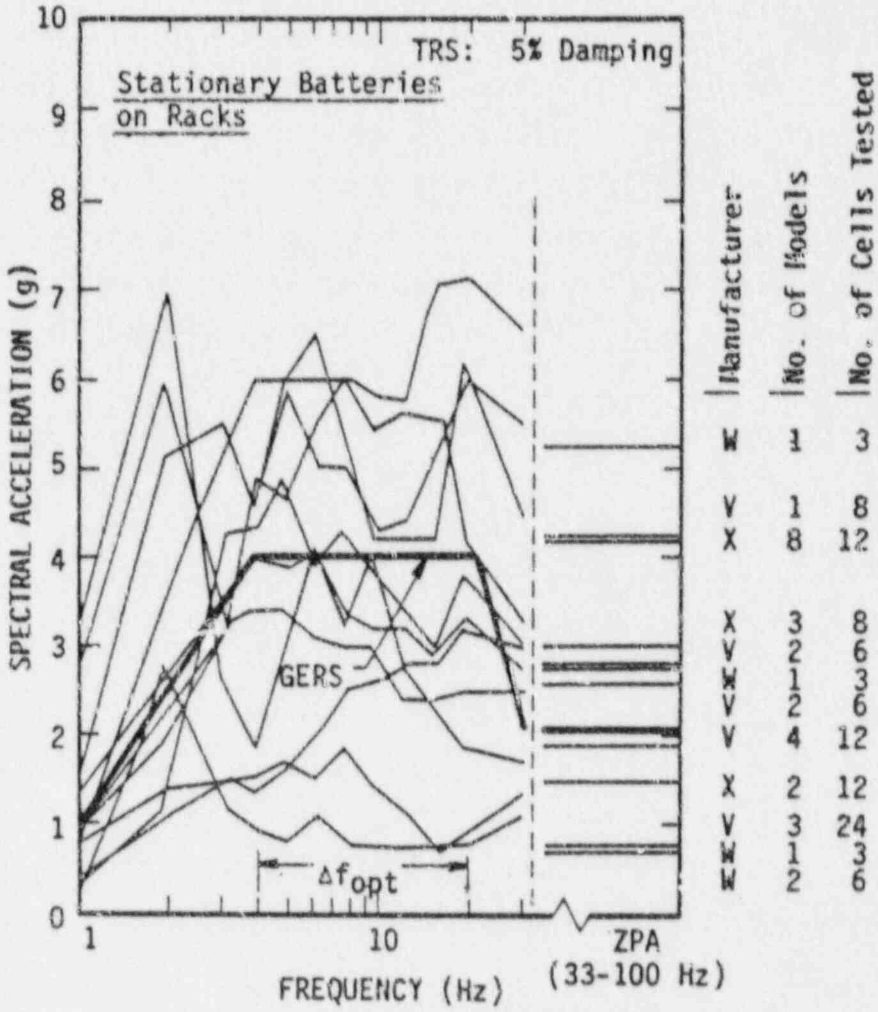
For each equipment class identified in Table 2, Reference [9] gives a corresponding composite spectrum generated from experience data. These spectra are termed "Generic Equipment Ruggedness Spectra" (GERS). The

TABLE 2. SPECIFIC EQUIPMENT CLASSES COVERED IN EPRI/ANCO STUDY FROM REFERENCE [9]

- Batteries on Racks
- Battery Chargers
- Inverters
- Motor Valve Operators
- Electrical Penetration Assemblies
- Pneumatic Timing Relays
- Distribution Panels
- Low-Voltage Switchgear
- Medium-Voltage Switchgear
- Transformers
- Motor Control Centers
- Control Panels
- Low-Voltage Contactors
- Auxiliary Relays-Socket
- Protective Relays-Panel
- Auxiliary Relays-Hinged Arm
- Auxiliary Relays-Industrial
- Switches
- Transmitters
- Instrument Rack Components
- Solenoid-Operated Valves
- Air-Operated Valves
- Safety Relief Valves
- Automatic Transfer Switches

conceptual approach for development of the GERS appears to be similar to the methods outlined herein in Paragraph 4.1.2, although sufficient detail is not presented to allow a point-by-point comparison. Generally, attention was paid to the frequency range which includes the natural frequencies noted in the low-level resonance tests for the equipment judged to be in a common subclass. This approach is analogous to what herein has been called noting the optimum frequency band for selection of Δf_{cc} (see Figure 6). One possible difference of the two methodologies lies in the weighting factors used to account for differences in test procedures. It is stated that a 0.7 modal interaction factor was used for narrowbanded (sine) data, while 1.0 was used for biaxial random data. The results presented herein in the examples of Paragraph 4.4 indicate that a 0.7 factor also may be appropriate for some especially-narrowbanded floor-level spectra, even though the tests may have been performed with random waveforms. Likewise, no details have been given herein relative to accounting for single-axis excitation. The 0.7 factor allowed in the GERS approach appears to be reasonable, and would similarly be applicable for the methods outlined herein. Finally, the methodology outlined herein generally uses success data for construction of composite spectra, while a GERS may include failure data as well. In both approaches, the composite spectra are based on proof test data and, as such, may be considered lower bound fragility data with an unspecified amount of conservatism included.

An example of a GERS developed for one- and two-step racks with stationary batteries is shown in Figure 12. Details of the logic behind how the composite spectrum (GERS) was drawn are not entirely clear from the report. However, as pointed out in the EPRI/ANCO approach, the degree of similarity of the equipment within the class has an important bearing on the process. That is, the "more similar" the data base equipment, the more liberal one can be in raising the level of the composite spectrum, providing that the component spectra allow an appropriate match within Δf_{opt}. As previously mentioned, the indicated optimum frequency range Δf_{opt} was established from judgments about the equipment dynamic characteristics. Likewise, a 0.7 correction factor was employed for reducing narrowband qualification data to an approximate equivalent broadband set which includes modal interaction.



NOTE: Δf_{opt} added for present report

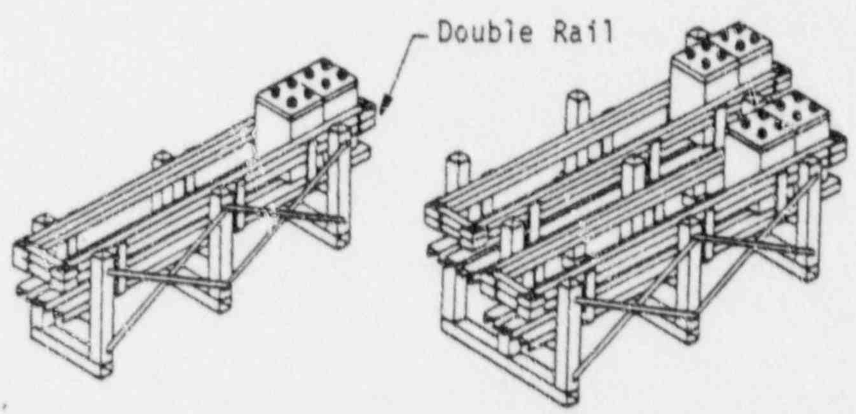
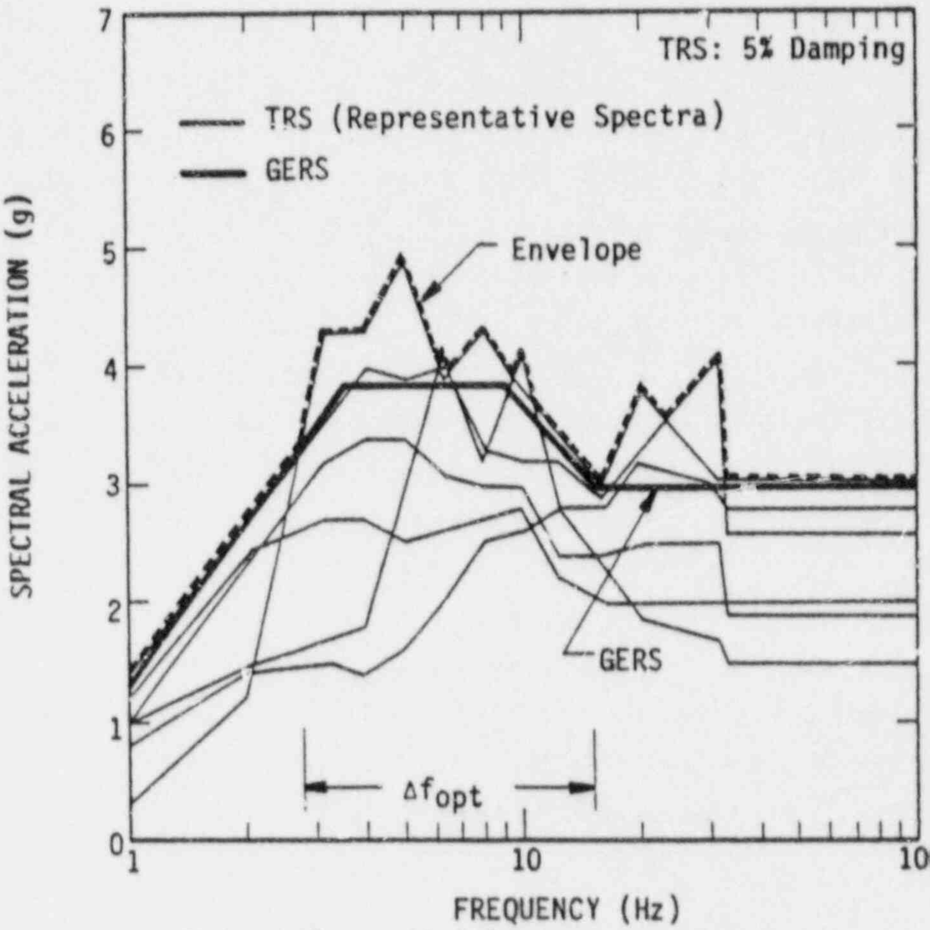


Figure 12. Comparison of GERS with TRS data: success data racks with stationary batteries (Reference 9)

It now becomes appropriate to ask how does one use the above data base? More specifically, how does one show that a new candidate item, for which no fragility (or qualification) data is available, is also qualified to the data base spectra? It becomes appropriate to consider the approach described in Paragraph 4.2, and show how the critical transfer function for the candidate item is similar to those of the data base equipment. Again, these details of the evaluation are not given in the EPRI/ANCO report. How ever, it would appear that the generic class of equipment includes various items, whose individual Δf_{ci} all fall within 4 Hz < Δf_{opt} < 20 Hz, as indicated in Figure 12. Furthermore, similarity of peak magnitudes for corresponding transfer functions in effect are approximately judged from weight, stiffness, and damping characteristics. Thus, the EPRI/ANCO approach and the similarity approach outlined herein appear to be analogous in principle, but the present approach emphasizes use of more detailed data.

A second example for generation of composite spectra taken from Reference 9 is given in Figure 13. Originally, the various component spectra correspond to equipment of low diversity (i.e., high similarity). If one were to generate the composite GERS by using the method proposed herein instead, only those component spectra that are above the GERS in Δf_{cc} would be used. Furthermore, it would be necessary to verify that Δf_{cc} falls within the optimum bandwidth Δf_{opt} indicated in the figure. Thereafter, those items whose component spectra are below the GERS in Δf_{cc} also would be considered qualified to the GERS level, providing that their individual Δf_{ci} fall within Δf_{cc}, and peak magnitudes of the $H_{pi}(f_{ci})$ have appropriate values. Thus, a more precise definition of Δf_{cc} and of critical transfer functions in this bandwidth constitutes the major difference between the present method and the EPRI/ANCO approach. For either approach, no matter how little data is used to generate the composite spectrum, comparison with additional data is very worthwhile to add confidence to the results.

Another approach to generic classification of equipment according to physical similarity has been reported in References [12,13]. Broadband fragility data are being generated for several classes of equipment. Modal



Note: Δf_{opt} added for present report.

Figure 13. Low diversity example. (Reference 9)

interaction correction factors are also employed. However, some difficulty exists for use of this data, as the rules for determining whether candidate items fit the physical similarity meant for each category are not yet fully explained.

The above examples illustrate groupings of equipment according to physical similarity at a level more approximate than that described in Paragraph 3.2.2. That is, Δf_{cc} and the various $H_{pi}(f_{ci})$ are only estimated from physical properties, rather than measured directly. On the other hand, more detailed verification of these parameters is probably possible if desired for the data base equipment, since various transfer functions are very likely available from resonance search data that was typically obtained during exploratory tests. Note also that the use of a rather broad Δf_{cc} has a tendency to reduce the amplitude of the amplified region of the composite spectrum. Nevertheless, an advantage of the broader Δf_{cc} is that it can include multiple Δf_{ci} for a given item of equipment, if such a condition exists. Thus, various composite spectra are possible, depending on the degree of physical similarity present in the equipment and the degree of excitation similarity in the component spectra. In a given situation, the use of certain spectra and equipment groupings may be more advantageous than others.

A final comparison to previously published information [8] concerns the use of actual qualification data which resulted from a proof test of an electrical cabinet. Figure 14 shows the magnitude plot for a transfer function of response measured on an interior panel during a base-excited resonance search. This location was judged to be the critical location, since it was near several control devices, even though failure never was actually experienced during the test. Figure 15 shows the RRS conservatively enveloped by the TRS for horizontal excitation during one SSE run of the seismic test.

It is now appropriate to consider whether there are other excitations for which the cabinet is also qualified. First, it is recognized that the TRS of Figure 15 can be considered an initial qualified FRS and is thereby

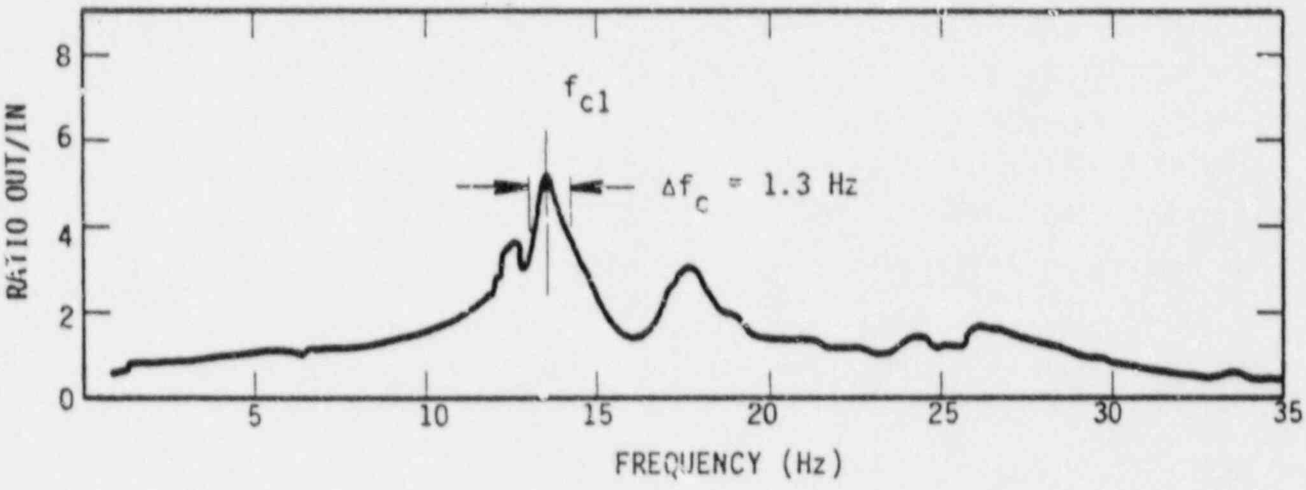


Figure 14. Transfer function for device input at critical location.

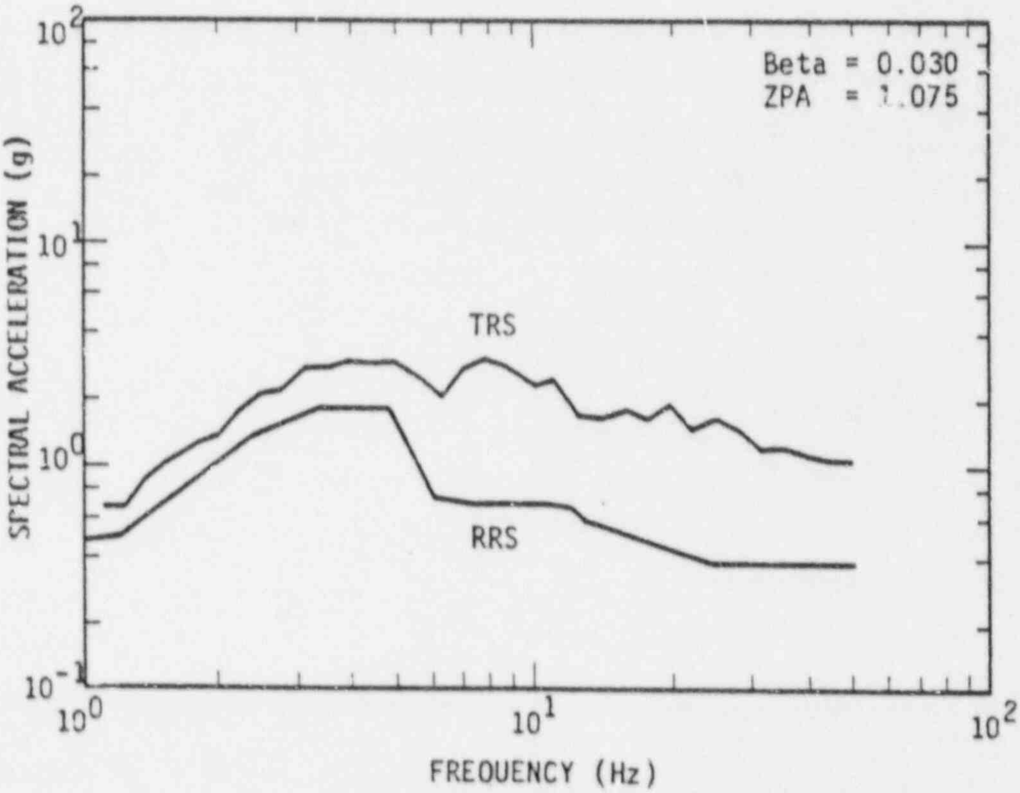


Figure 15. Conservative envelope of RRS by TRS for SSE horizontal excitation of electrical panel.

conservative to some unknown degree. Then, from Figure 14, the cabinet is judged to be a simple flexible item since only one dominant mode is present. Along with this, the item is judged to be failure-prone by a peak acceleration level that would occur primarily at the defined critical location. Therefore, in view of these judgments, adjustments to the TRS can be considered by means of spectral extension.

The critical transfer function in Figure 14 has a maximum amplification of 5.0 at 13 Hz and a damping of 5%. Therefore, A = 5 for A $R_p(f)$ defined in Paragraph 4.3.1. Furthermore, by assuring that Steps 1-5 of the same paragraph apply, two potential adjusted conditional fragility functions are shown in Figure 16. The adjusted site-specific FRS [illegible] of many for which the equipment can be qualified. This spectrum could have resulted from a new application or from the occurrence of an actual earthquake. The common requirement is that the peak spectral amplification ratio level of each corresponding waveform is nearly the same as that for the initial FRS, and the spectral values within Δf_{c1} at 13 Hz do not exceed that for the initial FRS. It may be noted that the peak spectral values for the adjusted Site Specific FRS in Figure 16 have been lowered compared to Figure 14 of Reference [8]. This was done to make the spectrum more compatible with waveform similarity requirements as defined herein. An adjusted standardized FRS is also shown. It is drawn by fitting a R.G. 1.60 spectrum to the original TRS also, so that the peak spectral amplification and spectrum requirements at 13 Hz are observed.

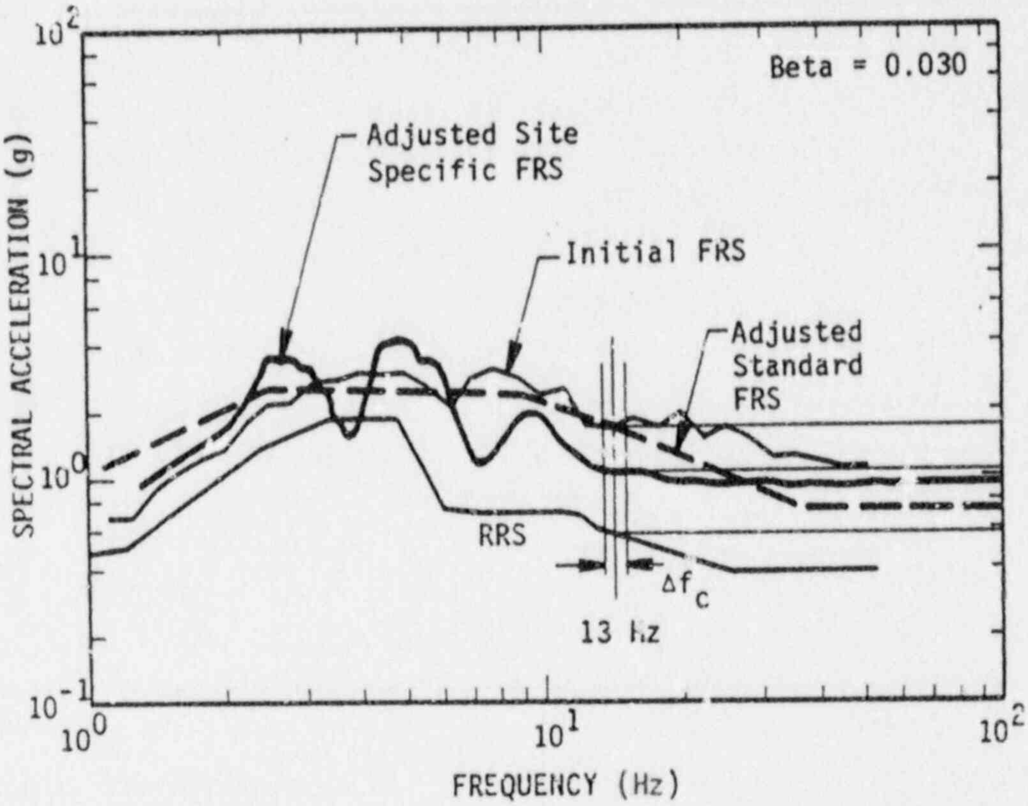


Figure 16. Adjusted qualified site specific and standard FRS for electrical panel.

6. SAFETY MARGIN APPLICATIONS

The developments in this document have been aimed primarily for use in typical equipment qualification scenarios. However, some indicated applications are appropriate for use in safety margin applications as well. Several programs are currently in progress to develop methods of determining seismic margin available in a nuclear plant. Two basic methods under development are described in References [14,15] and are identified as the Conservative Deterministic Failure Margin (CDFM) Method and the Fragility Analysis Method. Both methods allow the determination of whether a plant (as an aggregate of its equipment components and structures) can withstand a normal plus review seismic level earthquake. The review earthquake level is a maximum estimated level that could reasonably be expected to occur beyond the SSE (Safe Shutdown Level) and, at the same time, provide an indication of available margin. The Fragility Analysis Method requires generation of fragility data for groups of equipment, while the CDFM method avoids the requirement of actual fragility data, in that lower bound (or the usual proof qualification) data is used for the capacities of all of the various equipment and components. Specifically for equipment, in both methods composite spectra are required for groups of similar equipment. Composite spectra are formed and constitute an input to development of a High Confidence of Low Probability of Failure (HCLPF) acceleration value for each item or group of items of equipment.

To date, the use of GERS as a composite spectrum as developed in Reference [9], or composite fragility data as described in References [12,13], are typically used for the above described margin reviews. It is obvious that the procedures for composite spectra developed herein may also be considered. In particular, it is appropriate to determine whether the methods outlined herein provide any significant increase in seismic review level (i.e., increase in levels of the composite spectra). This can only be determined by a review of typical GERS and see whether the present methods allow development of more liberal composites. Furthermore, it is highly likely that the concept of spectrum extension will be especially useful in this application, since composite spectra may be extended to various site specific equipment locations. Again, a potential increase in equipment capacity level may result, with corresponding increase in probability of satisfactorily meeting a higher seismic review level.

7. DEMONSTRATION OF METHODOLOGY

The previous examples of methodology application introduced in this report have been based on what may be considered typical hypothetical equipment qualification scenarios. As such, some details which relate to actual equipment may therefore not have been included. Accordingly, several applications which deal with actual equipment and data available from its qualification will now be discussed. The examples are based on generic groups of equipment whose functional (operational) characteristics are very similar.

7.1 Instrument Panels

Given that a selection of existing qualification data for instrument panels is available, it is desirable to organize the data into a form that can be used to qualify by experience various subsequent designs of instrument panels, and to develop appropriate justification for the process. This means that similarity of the equipment group must be established and a composite spectrum developed. Basically, the principles outlined in Paragraph 4.1.2 are to be applied. However, when various data is available, more must be said about optimum selection of the data on which the composite is to be based.

Physical data for three wall-mounted and one floor-mounted instrument panels are given in Table 3. Additional qualification data for these panels are given in the subsequent figures. All panels indicated are of similar design, in that they include very nearly the same instrumentation devices mounted on different primary structures. Furthermore, Panels 1-3 are wall-mounted, while Panel 4 is floor-mounted. Nevertheless, it is stipulated that the critical functioning of each item is governed by a device mounted at the respectively-indicated critical locations, whose transfer functions coincide with those given in the available data. Note that not much physical data is given in the tables. In fact, not much is needed, since the primary description necessary to establish similarity resides in the critical transfer functions.

TABLE 3. PHYSICAL DATA FOR INSTRUMENT PANELS

Panel 1	
Description:	Wall-mounted electric control panel with approximately 30 components. Critical device located on an internal swing-out panel.
Dimension:	Enclosure: 36" (wide) x 16" (deep) x 48" (high) Swing-out panel: 36" (wide) x 20" (high)
Weight:	175 lb (Panel) + 75 lb (Components)
Response Location:	Near critical device located in the center of an internal swing-out panel. Swing-out panel located in the upper panel.
Failure Mode:	Relay chatter on critical device during and after seismic event for front-to-rear (X-axis) excitation.
Panel 2	
Description:	Wall-mounted electric control panel with approximately 20 components. Critical device located on an internal swing-out panel.
Dimension:	Enclosure: 36" (wide) x 16" (deep) x 48" (high) Swing-out panel: 36" (wide) x 24" (high)
Weight:	180 lb (Panel) + 59 lb (Components)
Response Location:	Same as above.
Failure Mode:	Same as above.
Panel 3	
Description:	Wall-mounted electric control panel with approximately 35 components. Critical device located on an internal swing-out panel.
Dimension:	Enclosure: 36" (wide) x 16" (deep) x 60" (high) Swing-out panel: 36" (wide) x 24" (high)
Weight:	220 lb (Panel) + 85 lb (Components)
Response Location:	Same as above.
Failure Mode:	Same as above.

TABLE 3. (continued)

Panel 4

Description:	Floor-mounted electric control panel with approximately 105 components. Critical device located on an internal swing-out panel.
Dimension:	Enclosure: 60" (wide) x 24" (deep) x 72" (high) Swing-out panel: 30" (wide) x 26" (high)
Weight:	1050 lb (Panel) + 260 lb (Components)
Response Location:	Near critical device located in the center of an internal swing-out panel. Swing-out panel located in the top right of the enclosure.
Failure Mode:	Same as above.

7.1.1 Composite Spectrum for Wall-Mounted Panels

Generally, in developing a composite spectrum for use as a reference data base, it will be most advantageous to select two reference equipment items whose functional (operational characteristics are quite similar, but whose critical transfer functions provide a relatively wide composite critical bandwidth Δf_{cc}. That is, the two items display relatively small similarity, such as Items 1 and 3 in Figure 4. At the same time, the two items should have been qualified to relatively high excitation levels. Furthermore, all individual spectra must be calculated at the same damping level for comparison purposes. It will be seen that this results in a relatively high level excitation composite which can be applied over a wide frequency range. Thus, the composite spectrum will be more generic in nature, and will be applicable to equipment having a wider range of dynamic characteristics. Therefore, the utility of the data base will be more extensive.

A composite spectrum is to be developed from the data for Panel 1, given in Figure 17, and that for Panel 2, given in Figure 18. The physical similarity of these two panels is established by the procedures given in Paragraph 3.2.2. Thus, a critical bandwidth from about 13 to 14.5 Hz is identified. (A wider band could not be established from available data.) Although the original test spectra were developed at different values of damping, they are all transformed to $\beta = 0.02$ by the following approximate relationship [9]:

$$R_{x1}(f)_2 = \sqrt{\beta_1/\beta_2}\, R_{x1}(f)_1$$

where $R_{x1}(f)2$ is an excitation response spectrum based on oscillator damping β_2 and $R_{x1}(f)1$ is the same spectrum based on oscillator damping β_1. Thus, the somewhat lower overall spectrum in Figure 18b becomes a composite spectrum, and is associated with frequency bandwidth $\Delta f_{cc}(1,2)$. Note that a 0.7 modal interaction correction is not applied since both original spectra are relatively broadband.

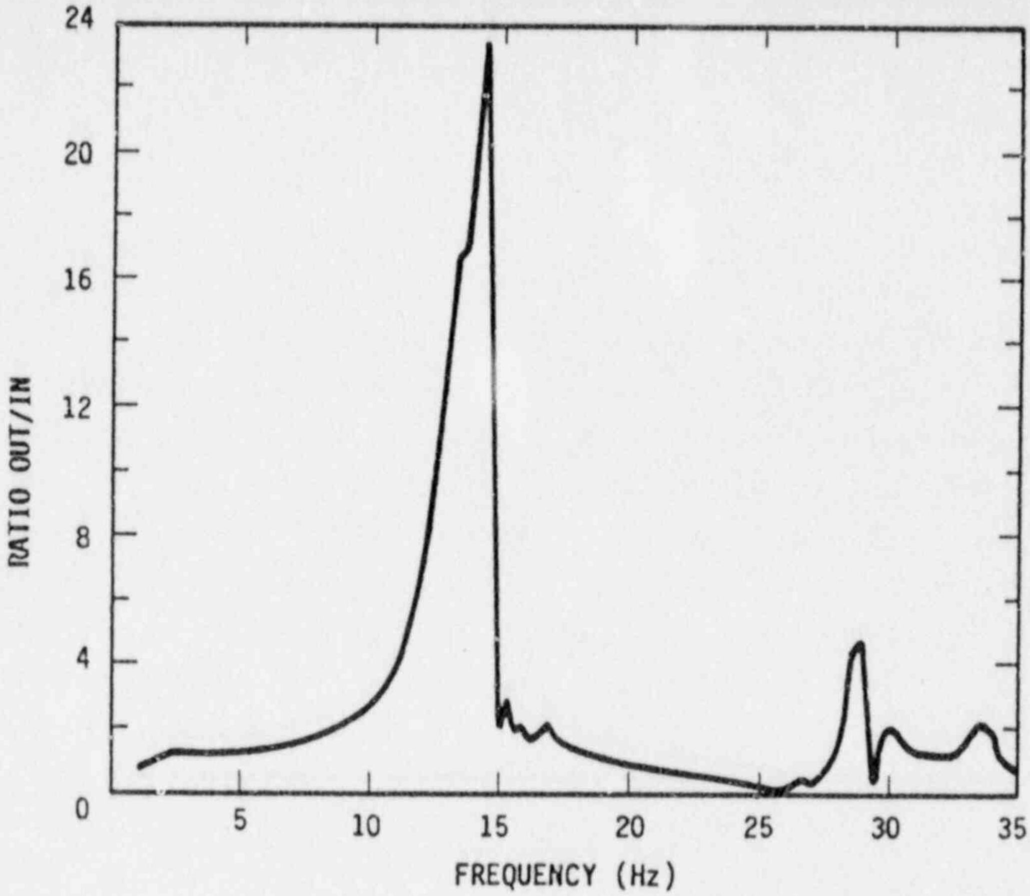


Figure 17a. Resonance search for Panel-1, X-axis, accelerometer on back of swing-out panel between Controllers, input 0.2 g peak, sweep 1.0 octaves/minute

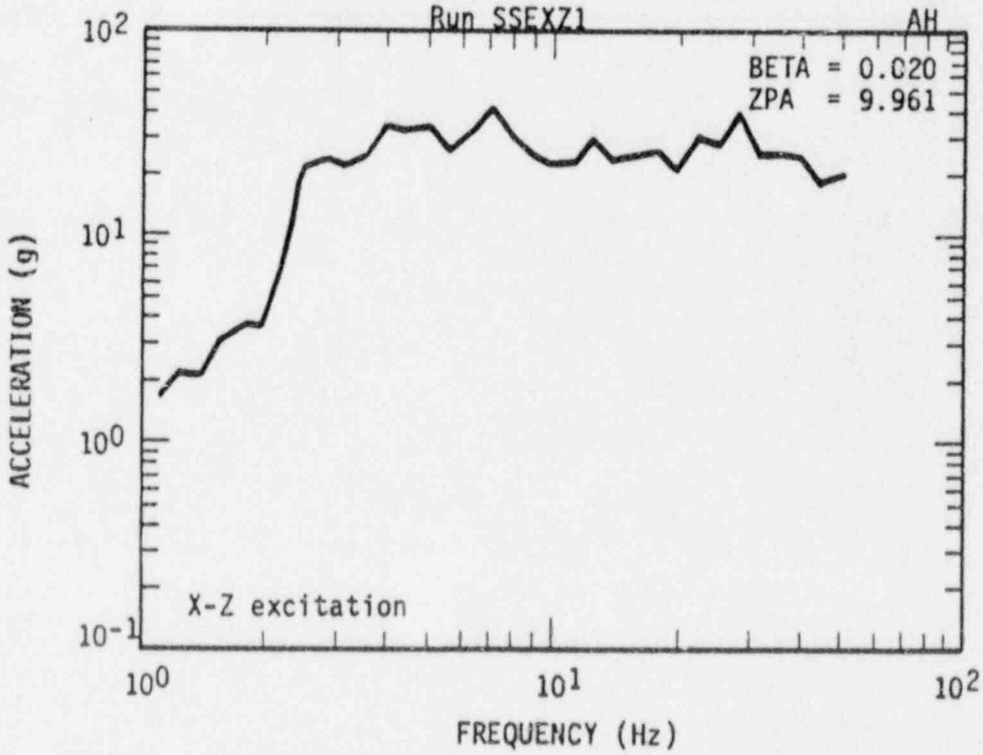


Figure 17b. TRS for qualification of Instrument Panel-1

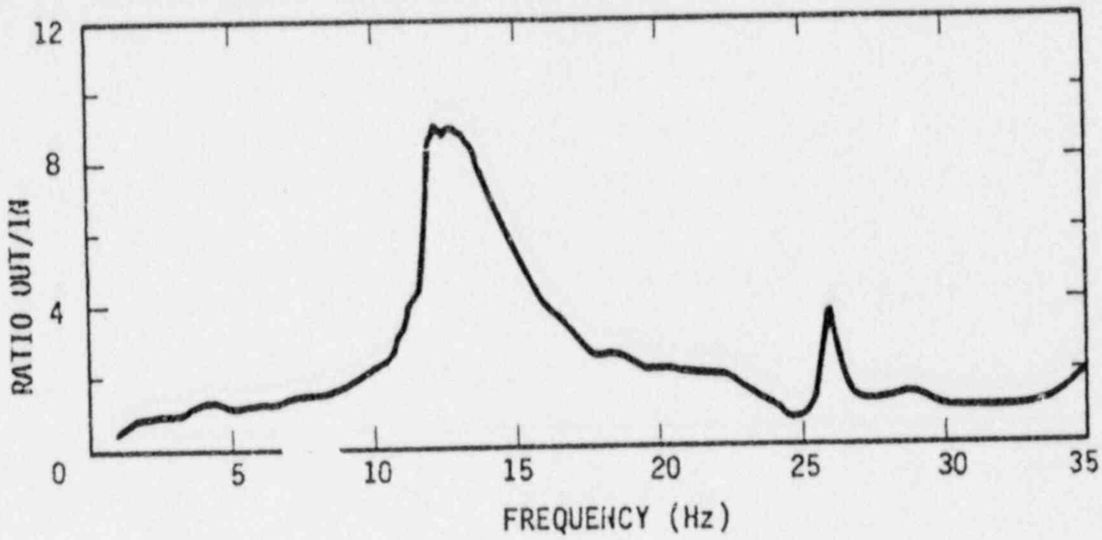


Figure 18a. Resonance search for Panel-2, X-axis, accelerometer located on front of the swing-out panel, input 0.2 g peak, sweep 0.5 octaves/minute

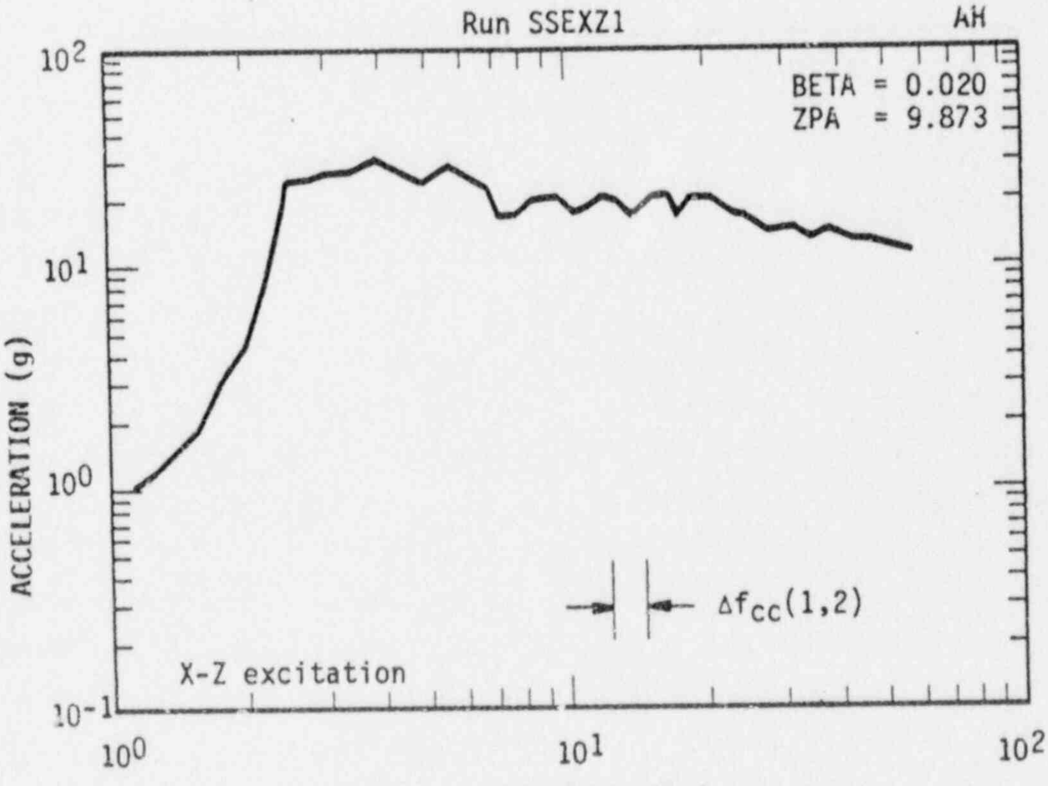


Figure 18b TRS for qualification of Instrument Panel-2 and composite spectrum

In the present case, $\beta = 0.02$ was used because most of the original spectra were calculated for this damping. However, eventually, when large volumes of data are handled for various types of equipment, a standardized value of $\beta = 0.05$ may be desirable [9]. It may further be noted that having established the composite spectrum, any physically similar panel is now qualified to this spectrum.

7.1.2 Qualification Upgrade for Panel 3

Now consider the qualification by experience for Panel 3, whose previous qualification data is given in Figure 19. By inspecting the critical transfer function of Figure 19a and the data of Table 3, it can be argued that Panel 3 is physically similar to the data base (i.e., Panels 1 and 2). Note that Panel 3 has previously been qualified to the relatively low spectrum given in Figure 19b. However, because of similarity, by experience, it can now be argued that it is also qualified to the much higher composite spectrum given in Figure 18b.

7.1.3 Verification for Methodology

Qualification data which tends to verify the experience approach for this equipment is given in Figures 20 and 21. Figure 20a gives the critical transfer function for Panel 4, which is a floor-mounted panel (the transfer function is repeated in Figure 21a for convenience). Although this is a floor-mounted versus a wall-mounted panel, by following the principles in Paragraph 3.2.2, it can be established that this panel is physically similar to Panels 1,2. (Note that a slight stretch of the rules is necessary for the low side of $\Delta f_{cc}(1,2)$.) Figure 20b gives a test spectrum to which Panel 3 has been qualified. Note that this spectrum falls at or below the composite spectrum given by Figure 18b. Thus, the similarity approach is verified for this case. On the other hand, Panel 3 was found to malfunction by a critical device near the critical location, when it was subject to the spectrum given in Figure 21b. By comparing this spectrum with the composite given in Figure 18b, it can be seen that the

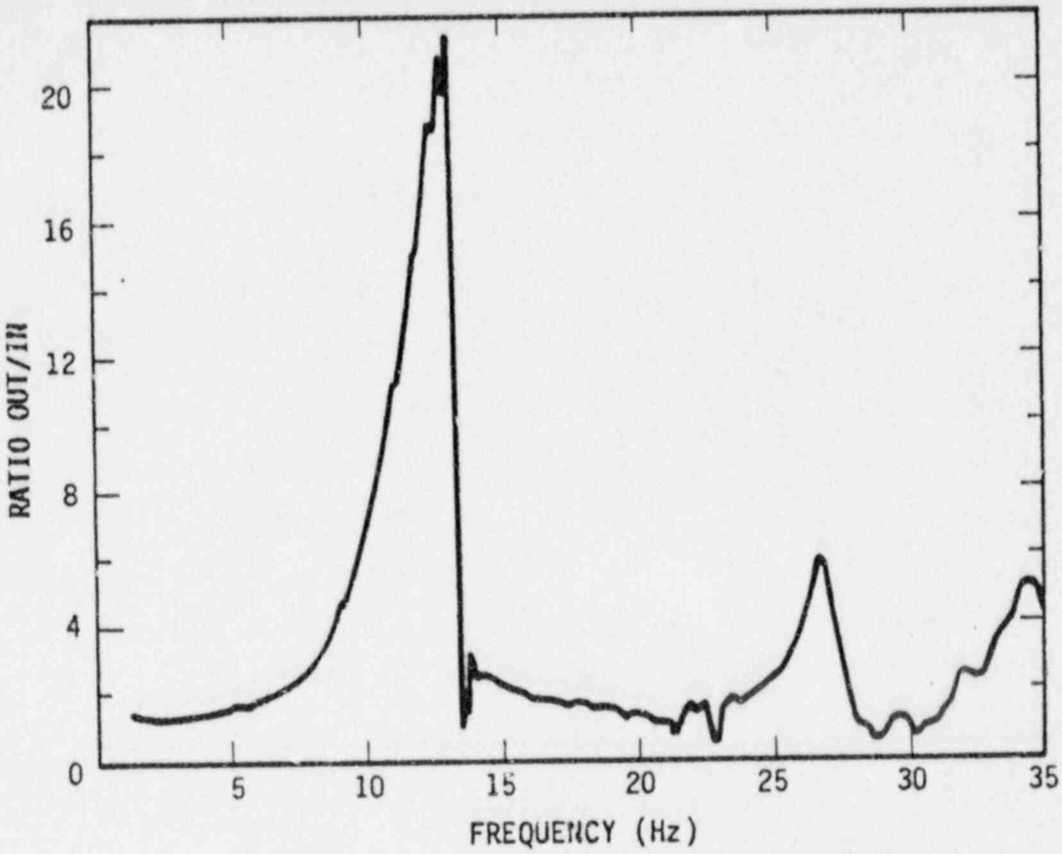


Figure 19a. Resonance search for Panel-3, X-axis, accelerometer on back of swing-out panel near Controller X-1.3, input 0.2 g peak, sweep 1.0 octaves/minute

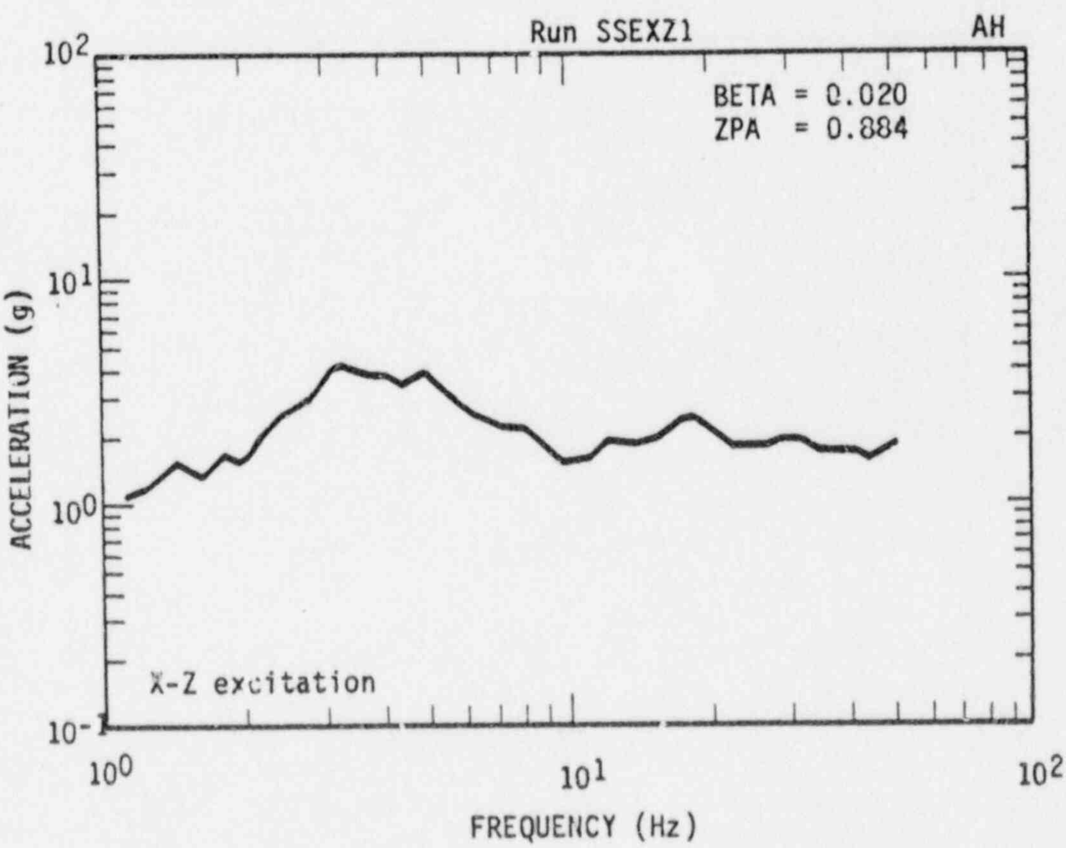


Figure 19b. TRS for qualification of Instrument Panel-3

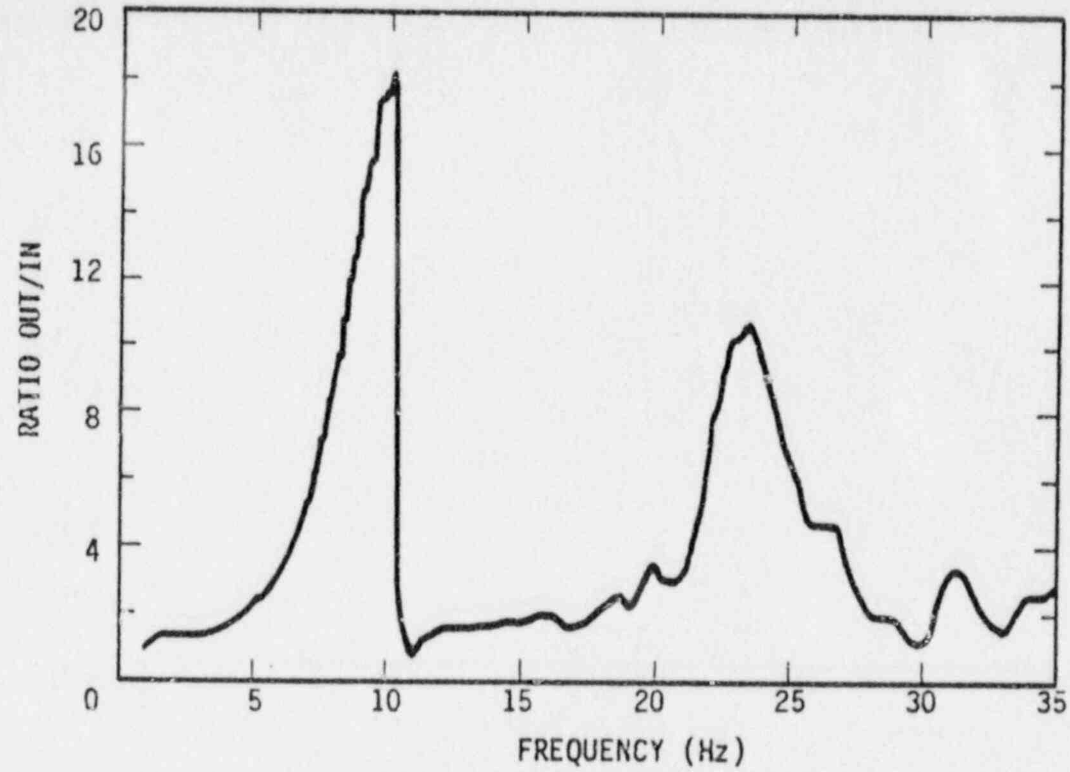


Figure 20a. Resonance search for Panel-4, X-axis, accelerometer on swing-out panel, input 0.2 g peak, sweep 1.0 octave/minute

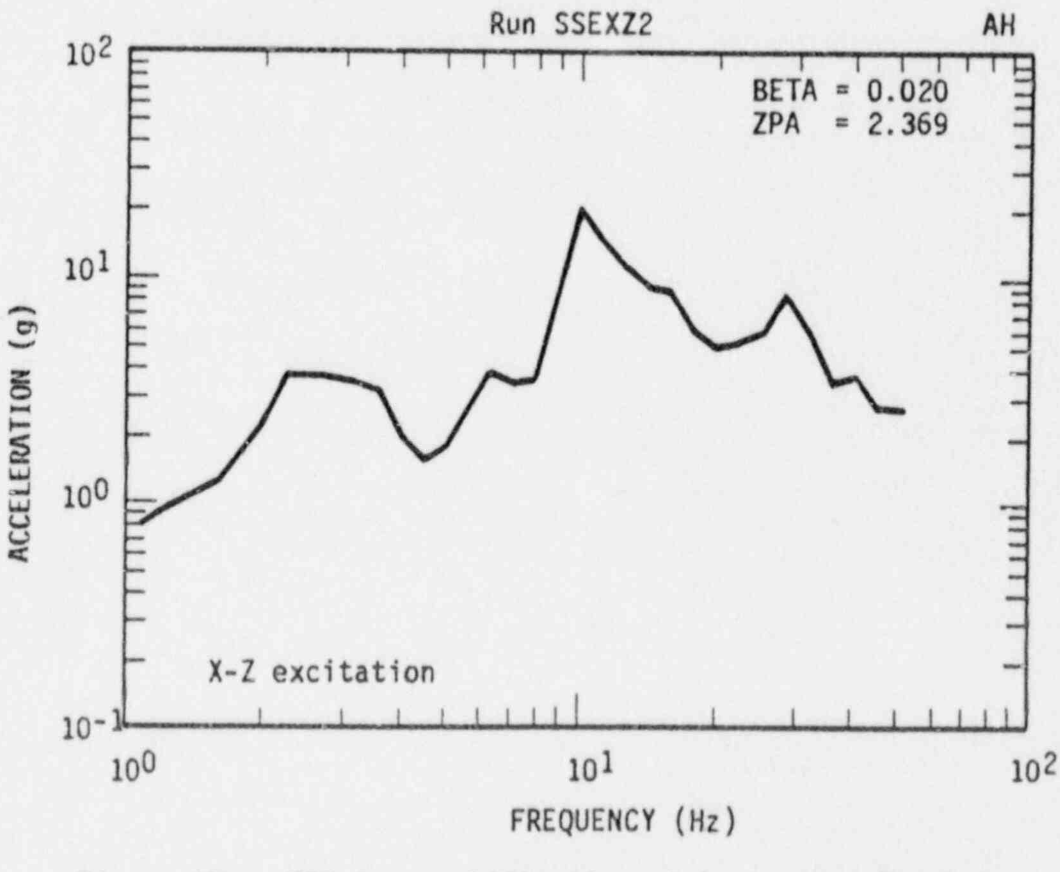


Figure 20b. TRS for qualification of Instrument Panel-4, qualification successful

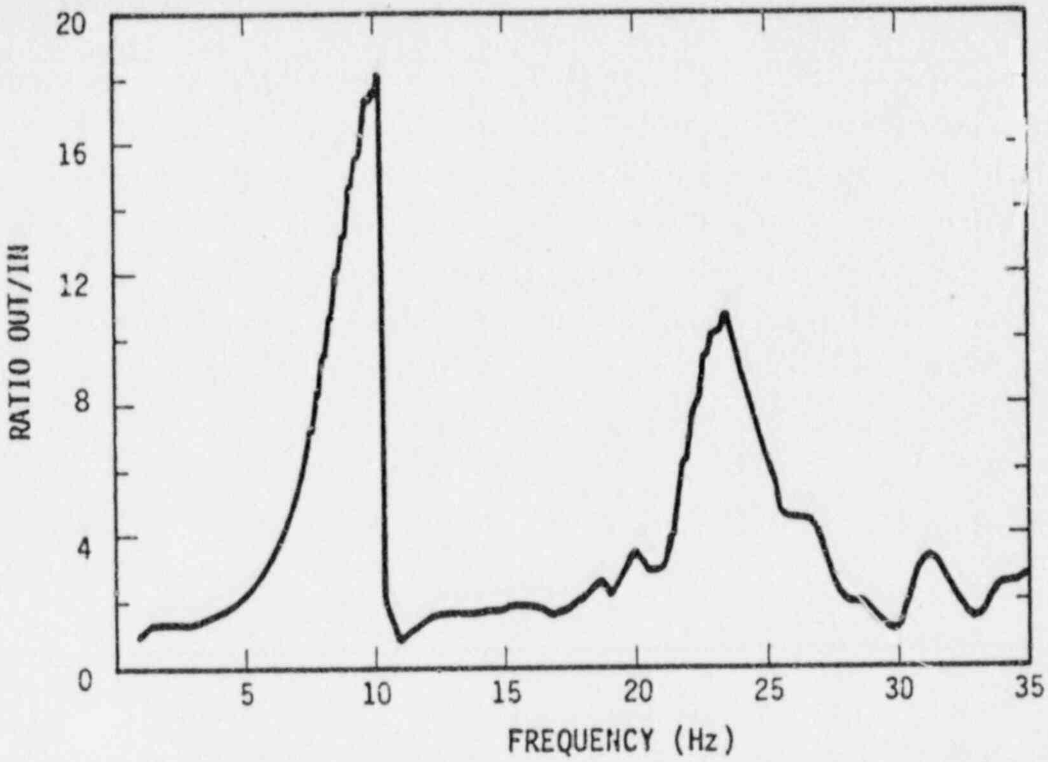


Figure 21a. Resonance search for Panel-4, X-axis, accelerometer on swing-out panel, input 0.2 g peak, sweep 1.0 octave/minute

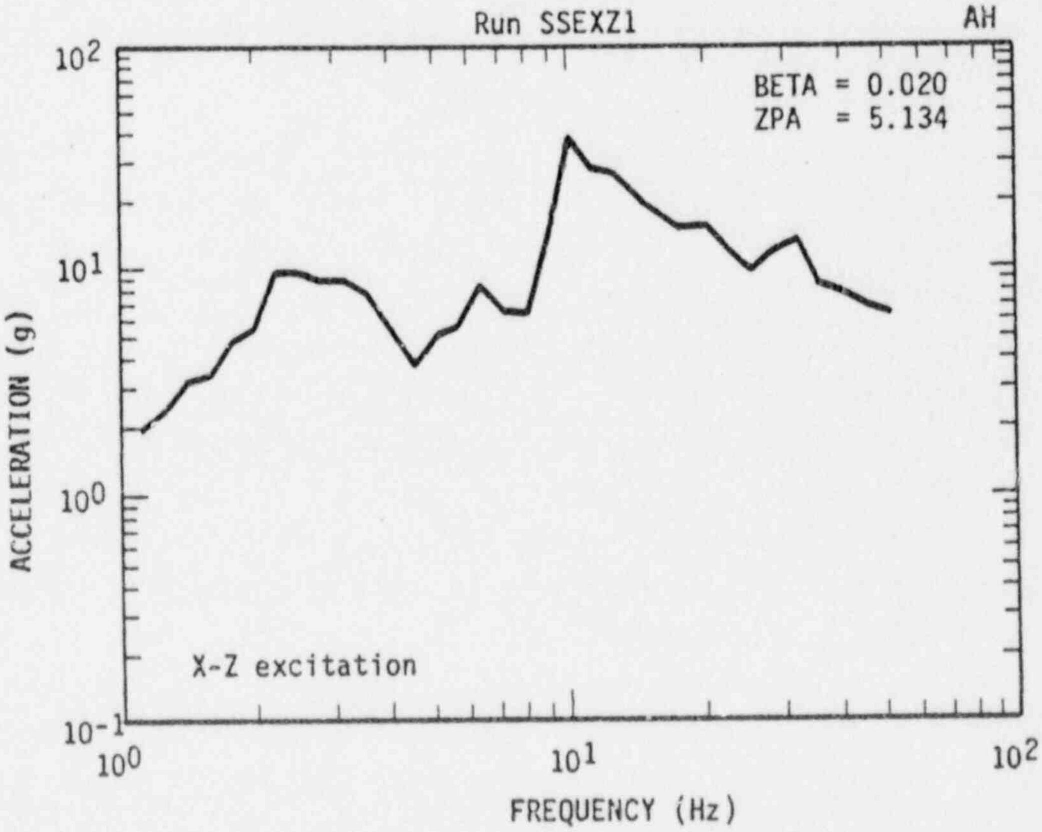


Figure 21b. TRS for qualification of Instrument Panel-4, qualification failed

test spectrum failed by the panel has a response of about 30 g within Δf_{cc}, which exceeds the response of about 20 g for the composite spectrum in this frequency band. Note also that the 30 g response in Δf_{cc} for Figure 21b also exceeds the approximate 25 g response for Figure 17b, as one would also expect, since Panel 1 passed the qualification. Thus, a verification of the process is provided. Furthermore, the fragility level for all four panels within the frequency increment $\Delta f_{cc}(1,2)$ has been established by this data. It is very likely that the spectrum of Figure 17b can be considered a good approximate lower-bound fragility response spectrum from these developments.

7.2 Motor-Operated Valves

Table 4 presents physical data for three motor-operated valves, and corresponding previous qualification data are given in Figures 22-24. These data were selected from various other qualification data in existing files. An inability for an operator to open or close its valve within prescribed time limits was considered the primary mode of failure. In all cases, the transfer functions were acquired at a location near the motor-operator. Thus, they represent critical transfer functions for the respective items.

For this example, consider that Valve 1 and Valve 2 are reference items. For this, a composite critical bandwidth $\Delta f_{cc}(1,2)$ extends from about 9.5 Hz to 15 Hz. The qualification spectrum for Valve 1 (Figure 22b) is very high, even though it is computed at 5% damping. It completely envelopes the spectrum for Valve 2 (Figure 23b), which is computed at 2.5% damping. Thus, Figure 23b becomes a composite spectrum at 2.5% damping. It is not reduced by a 0.7 factor, since both spectra are broadband. As a composite spectrum, it can be used to qualify other similar valves. This can be verified by the data from Valve 3, which can be seen to be similar by examining its critical transfer function (Figure 24a). The procedures assert that Valve 3 is also qualified to the composite spectrum (Figure 23b). This assertion is verified by noting that Valve 3 was previously qualified to the spectrum in Figure 24b, and the latter spectrum

TABLE 4. PHYSICAL DATA FOR MOTOR-OPERATED VALVES

Valve 1

Description:	3 inch, 150 lb control valve with operator.
Dimension:	48 inches high.
Weight:	180 lb (Valve with operator)
Response Location:	Valve yoke near stem/operator interface.
Failure Mode:	Inability for operator to open and close gate (plug) during and after seismic event for X-Z excitation.

Valve 2

Description:	3 inch, 900 lb control valve with operator.
Dimension:	54 inches high.
Weight:	350 lb (Valve with operator)
Response Location:	Valve yoke near stem/operator interface.
Failure Mode:	Inability for operator to open and close gate (plug) during and after seismic event for X-Z excitation.

Valve 3

Description:	3 inch, 900 lb Buttweld control valve.
Dimension:	60 inches high.
Weight:	375 lb (Valve with operator)
Response Location:	Valve yoke near stem/operator interface.
Failure Mode:	Inability for operator to open and close gate (plug) during and after seismic event for X-Z excitation.

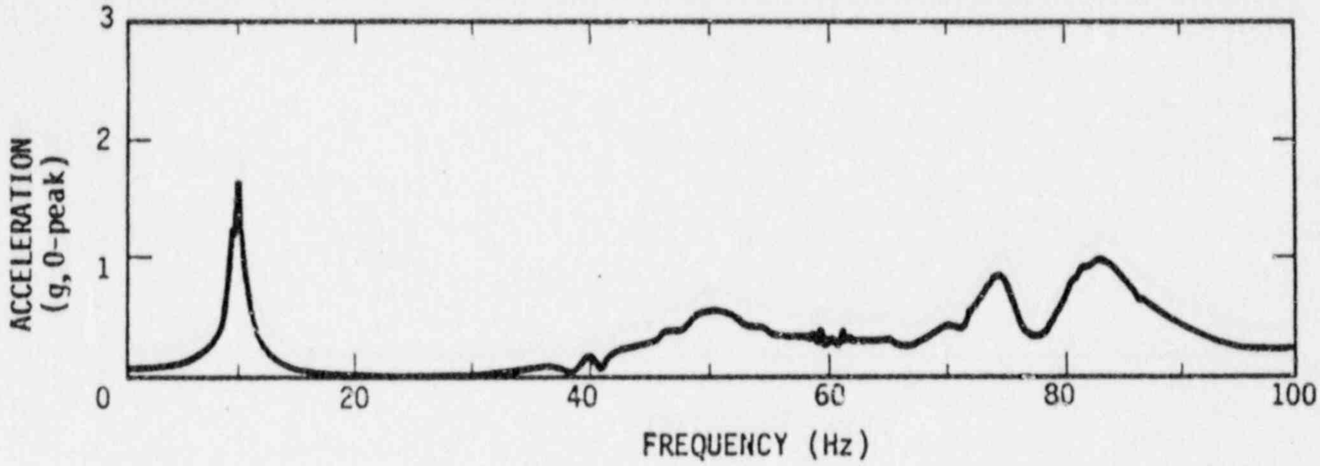


Figure 22a. Resonance search of Valve-1 for Y-axis excitation, valve opened position, 0.2 g input

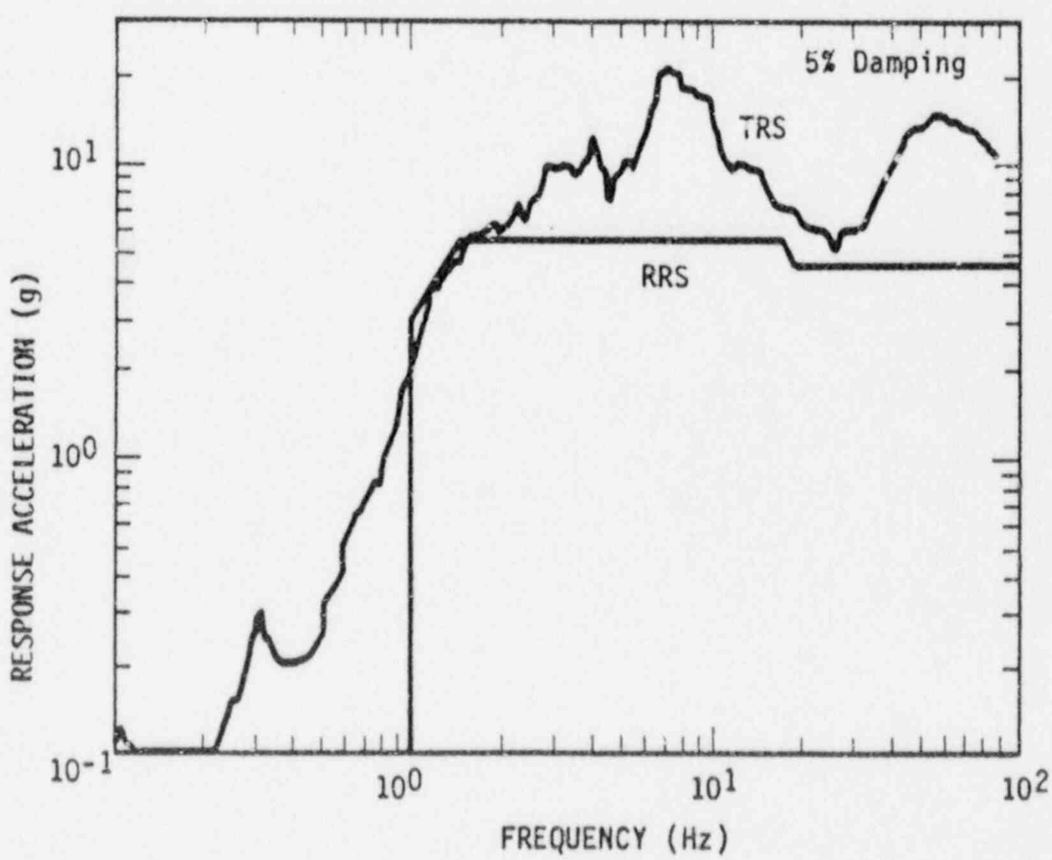


Figure 22b. Response spectrum for qualification of Valve-1

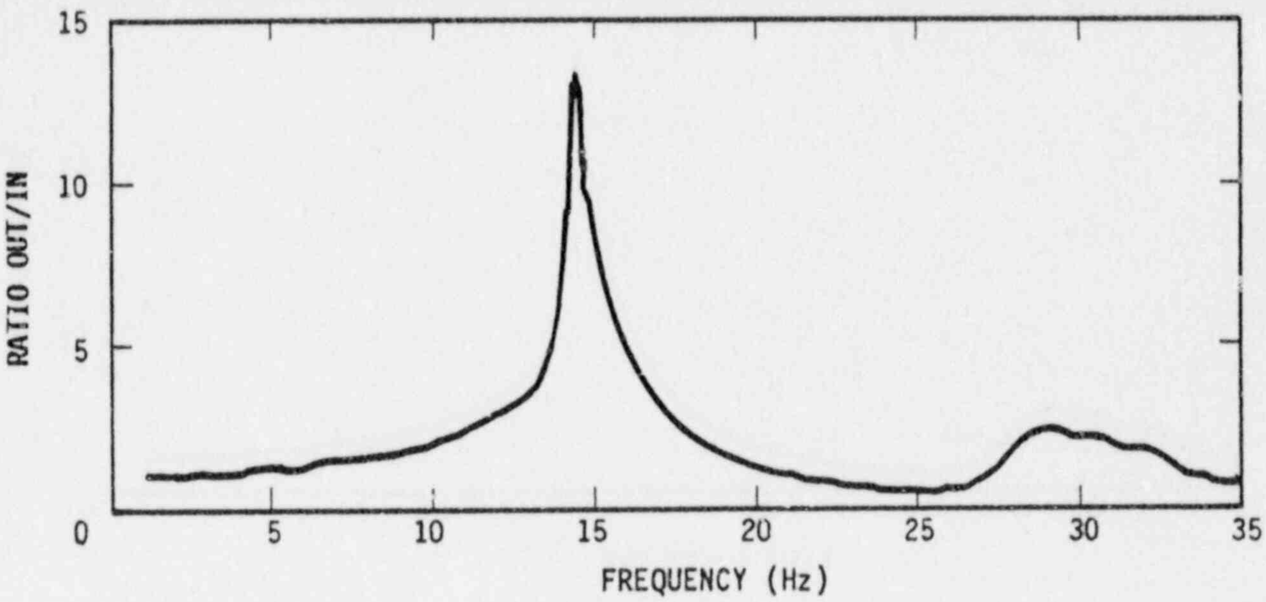


Figure 23a. Resonance search for Valve-2, monitor actuator CG, Y-axis, 0.2 g input

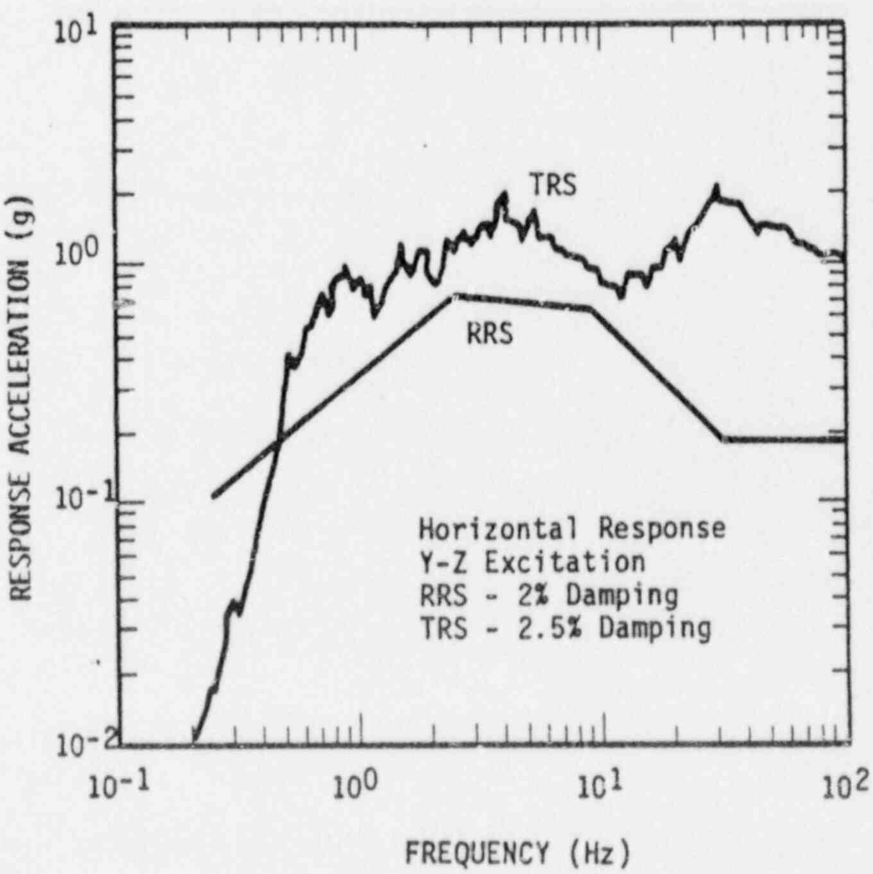


Figure 23b. Response spectrum for qualification of Valve-2

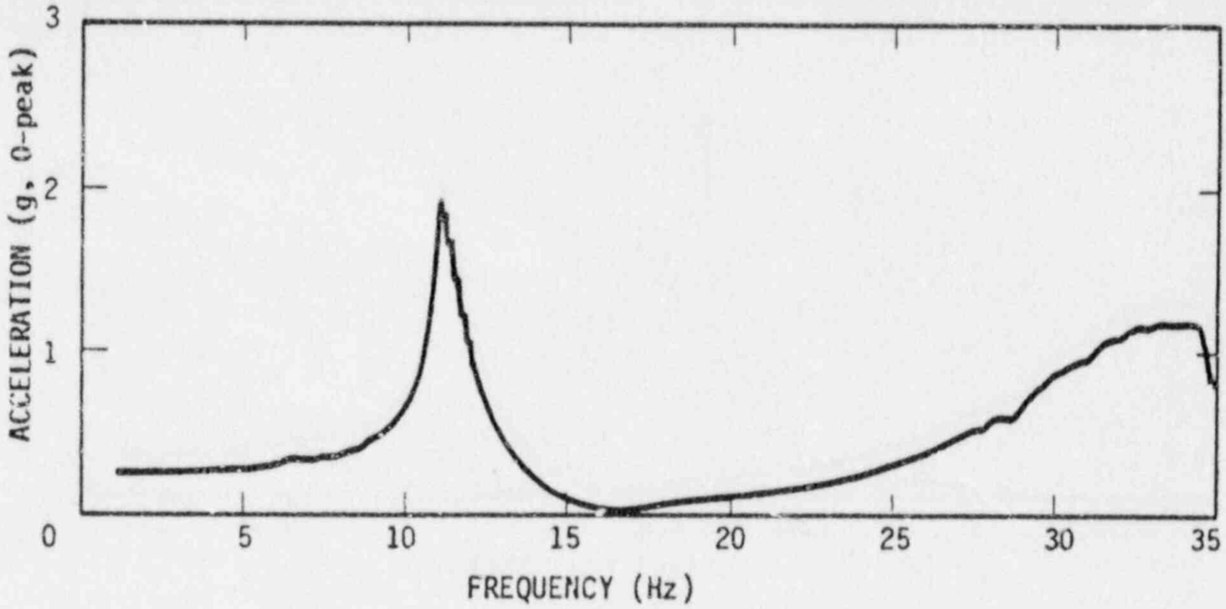


Figure 24a. Resonance search for Valve-3, Y-axis, valve open, 0.2 g input

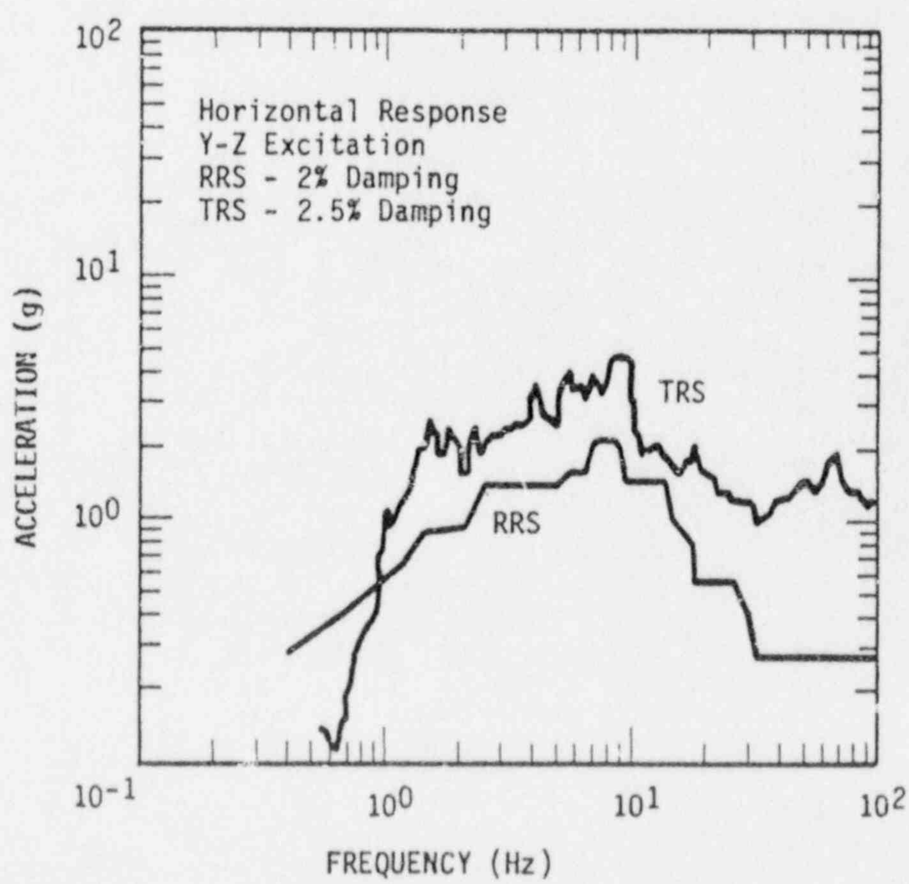


Figure 24b. Response spectrum for qualification of Valve-3

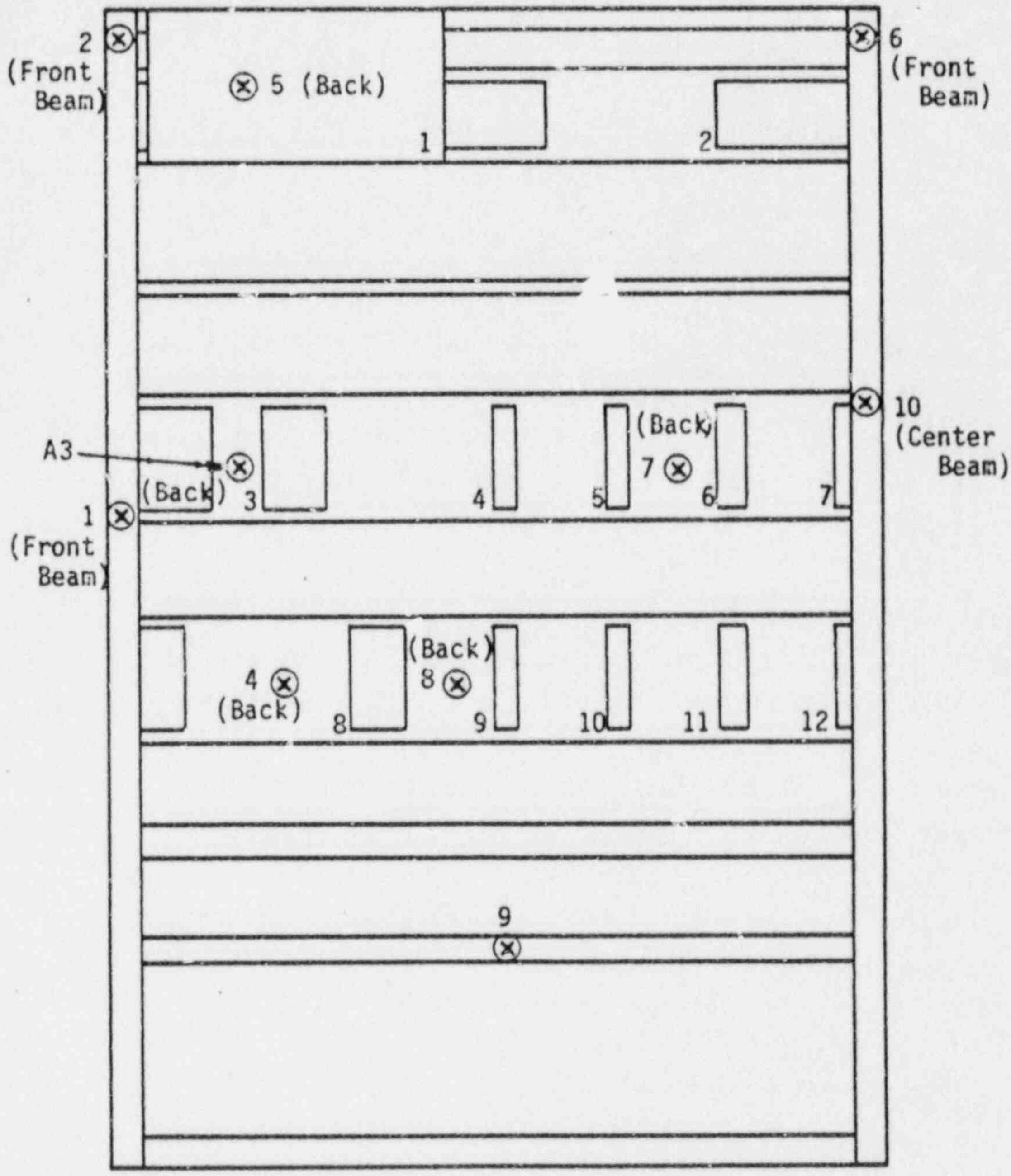
envelopes the composite spectrum (Figure 23b) over all but the high frequency range above about 30 Hz. Thus, had Valve 3 been a candidate item with no previous qualification, its qualification by similarity would be assured to the composite spectrum as stated.

7.3 Instrumentation Local Panels

The previous two examples have dealt with a relatively straightforward development of a composite spectrum for subsequent use in qualifying other candidate items. The next example will demonstrate the use of spectrum extension for a special case where additional qualification data is available.

First, consider a qualification which was performed on a 48" local panel, a diagram for which is shown in Figure 25. Physical data for this panel is shown in this figure as well as in Table 5. During a test series for this panel, it was qualified to the spectrum (Test Run 003) shown in Figure 26a. Furthermore, it was found that Device 3 (i.e., Yarway 4418C Level Indicator Switch) malfunctioned for the test run indicated by the spectrum shown in Figure 26b, which can be considered a fragility response spectrum for this panel. A critical elevated location response spectrum, taken at location A3 for the qualification Run 003 is shown in Figure 27, while a critical transfer function for location A3 is shown in Figure 28.

Now, in addition to the above-indicated qualification on the instrumented 48" panel, at a different time additional tests were run on mockups of this same panel and two other panels of slightly different sizes. The mockups consisted of the actual panel primary structure, but only dummy instruments were installed. Typical data for the other two panels is also given in Table 5, and critical transfer functions at locations which correspond to A3 on the 48" panel, are given for the other two panels in Figure 29 and 30. Furthermore, elevated response spectra for location A3 and the excitation response spectra are given in Figures 31-33 for the subsequent tests on each mockup panel with dummy instruments.



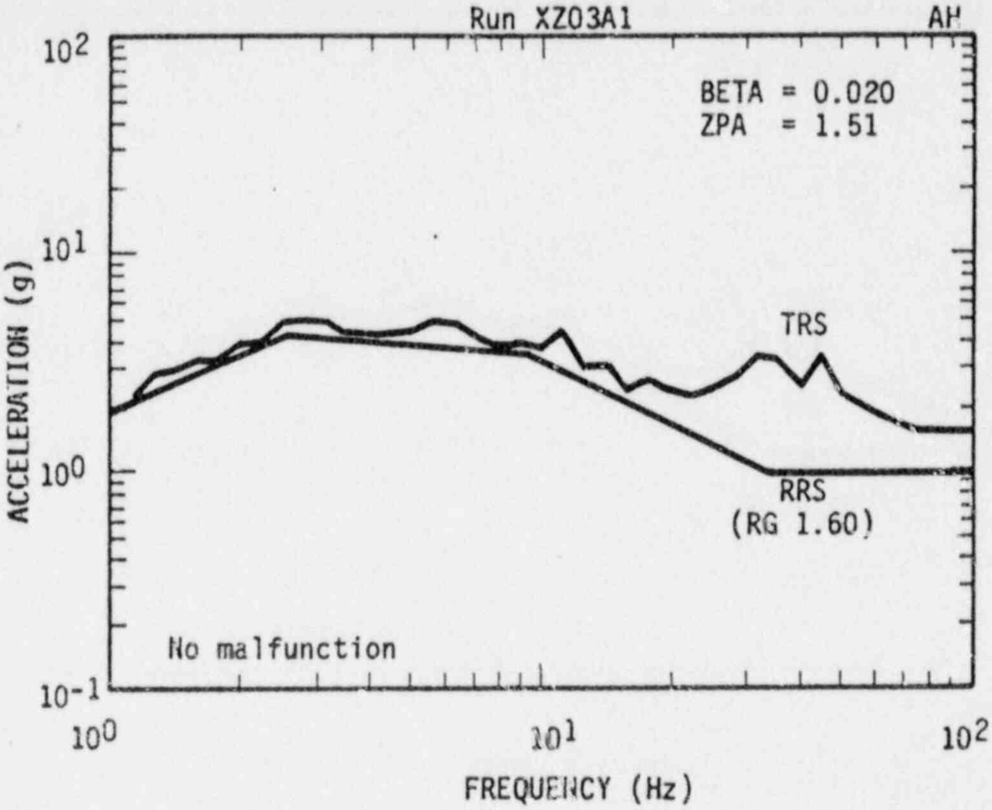
1. NEMA Box (Large)
2. NEMA Box (Small)
3. Yarway 4418C Level Indicator Switch
4. Dummy Instrument
5. Dummy Instrument
6. Barksdale D2H-M80SS
7. Dummy Instrument
8. Rosemount 535E
9. Robertshaw SP-222-C
10. Dummy Instrument
11. Dummy Instrument
12. Dummy Instrument

⊗ Accelerometer Locations

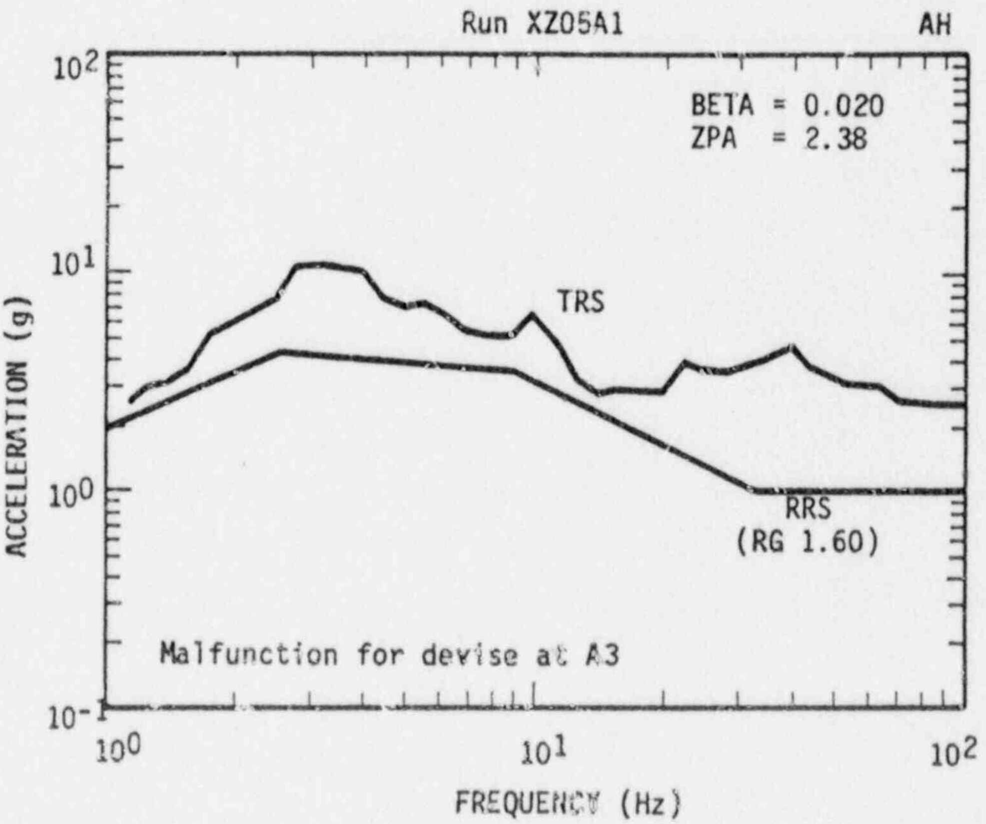
Figure 25. Instrument arrangement for 48" Local Panel

TABLE 5. PHYSICAL DATA FOR LOCAL PANELS

48" Local Panel	
Description:	48" wide Mock Local Instrument Panel. Approximately 12 instruments and dummy instrument weights were mounted on the panel (see Figure 25) for first qualification. Twelve (12) dummy instruments were installed for second test series.
Dimension:	48" (wide) x 30" (deep) x 94" (high).
Weight:	650 lb (Panel) + 36 lb (Instruments)
Response Location:	Left front corner approximately two-thirds up from base.
Failure Mode:	Switch chatter on Yarway 4418C Indicator due to high peak acceleration for X-Z (front-rear/vertical) excitation.
30" Local Panel	
Description:	30" wide Mock Local Instrument Panel. Approximately 6 dummy instrument weights were mounted on the panel.
Dimension:	30" (wide) x 30" (deep) x 94" (high).
Weight:	550 lb (Panel) + 20 lb (Instruments)
Response Location:	Left front corner approximately two-thirds up from base.
Failure Mode:	Mechanical failure due to high peak acceleration for X-Z (front-rear/vertical) excitation.
72" Local Panel	
Description:	72" wide Mock Local Instrument Panel. Approximately 19 dummy instrument weights were mounted on the panel.
Dimension:	72" (wide) x 30" (deep) x 94" (high).
Weight:	720 lb (Panel) + 138 lb (Instruments)
Response Location:	Left front corner approximately two-thirds up from base.
Failure Mode:	Mechanical failure due to high peak acceleration for X-Z (front-rear/vertical) excitation.



a. TRS envelope of RRS for Run 003 for 48" Local Panel



b. TRS envelope of RRS for Run 005 for 48" Local Panel

Figure 26. Fragility data for 48" Local Panel

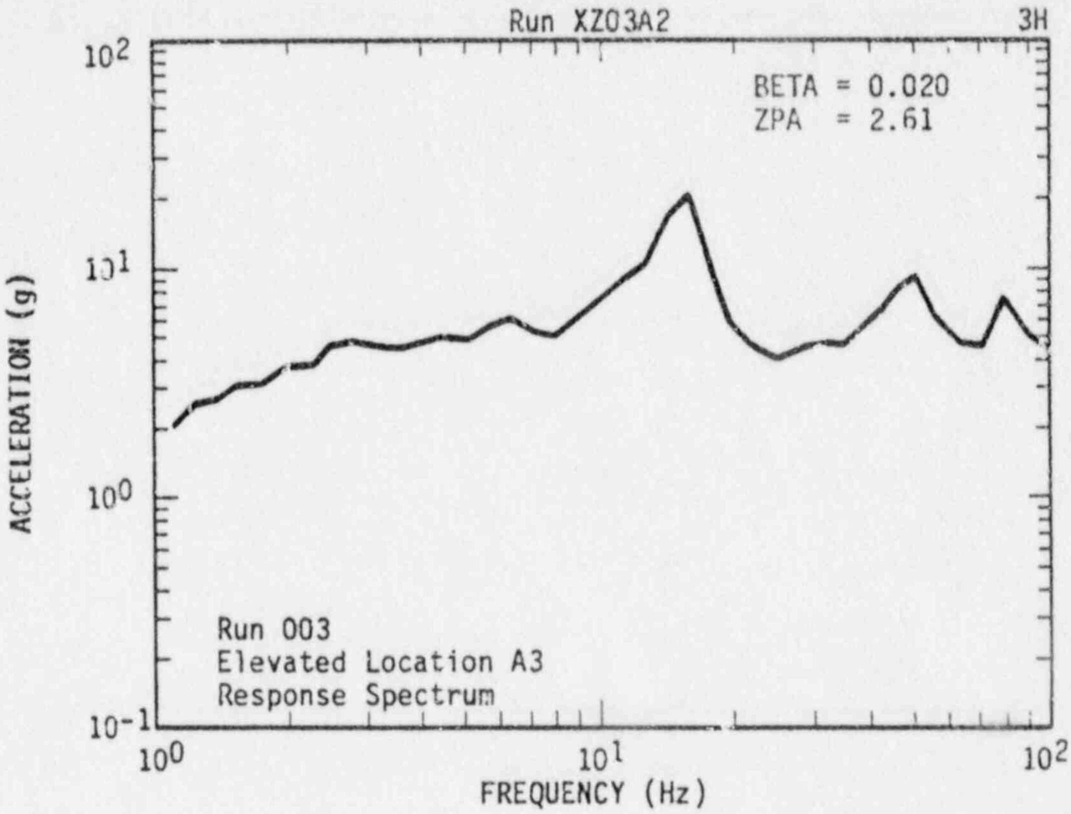


Figure 27. Elevated location response for 48" Local Panel

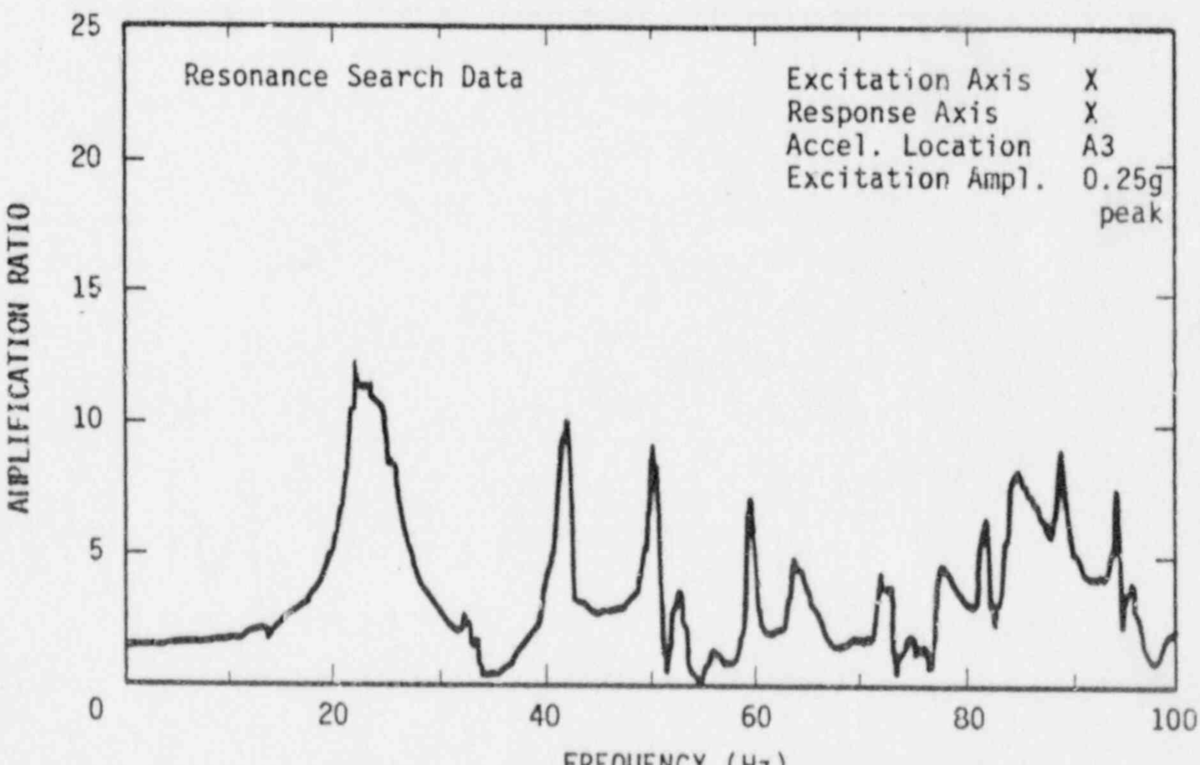


Figure 28. Location A3 transfer function for 48" Mockup Panel

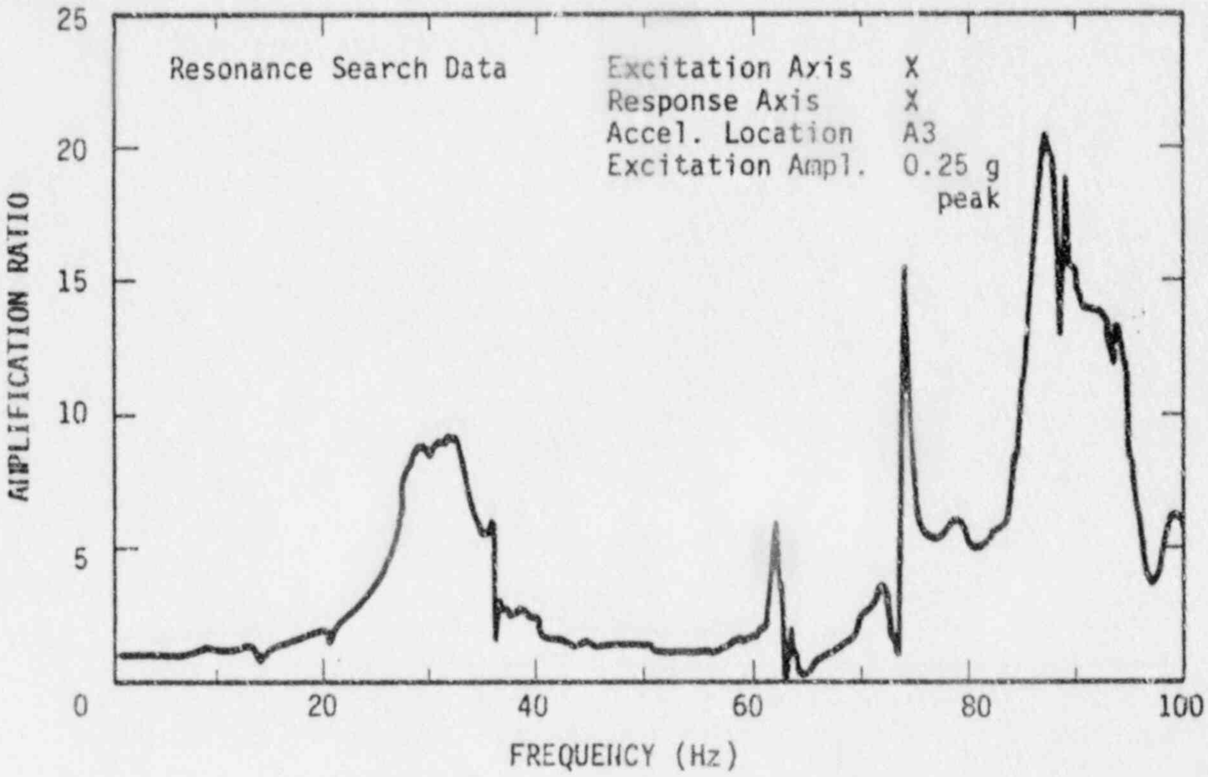


Figure 29. Location A3 transfer function for 30" Mockup Panel

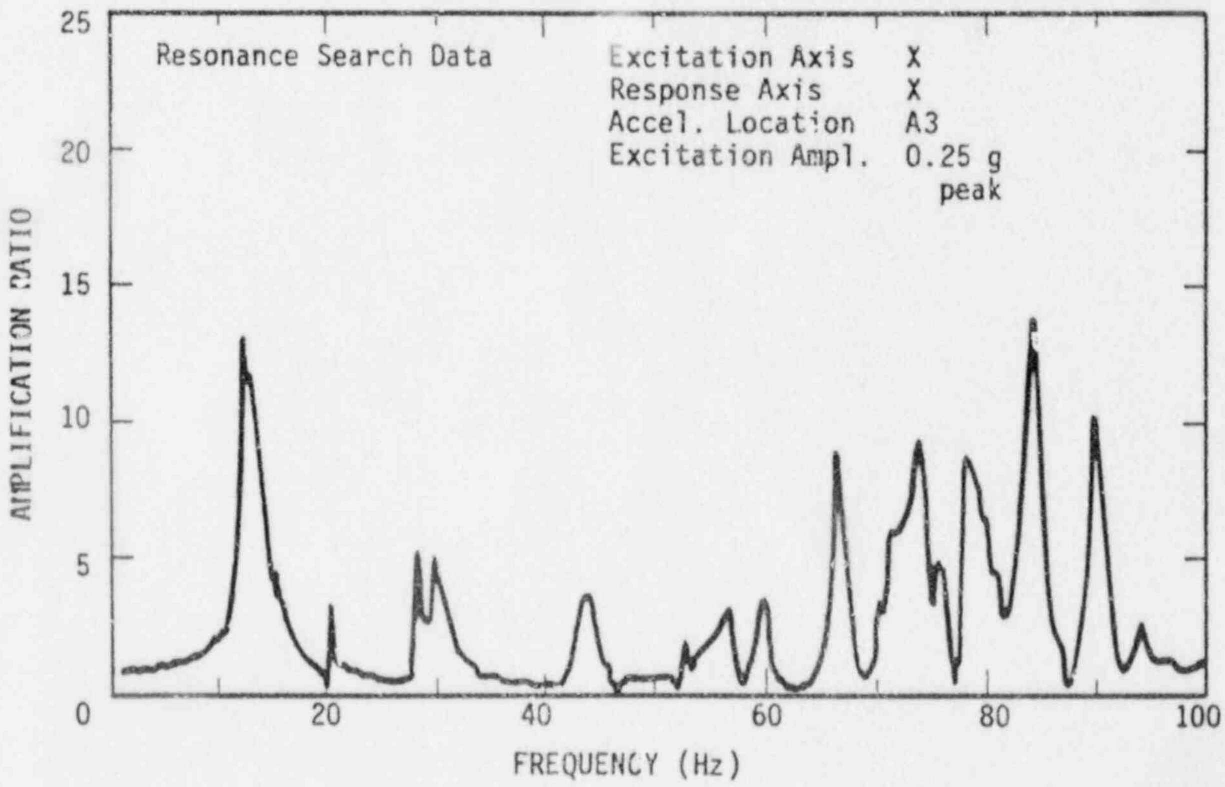
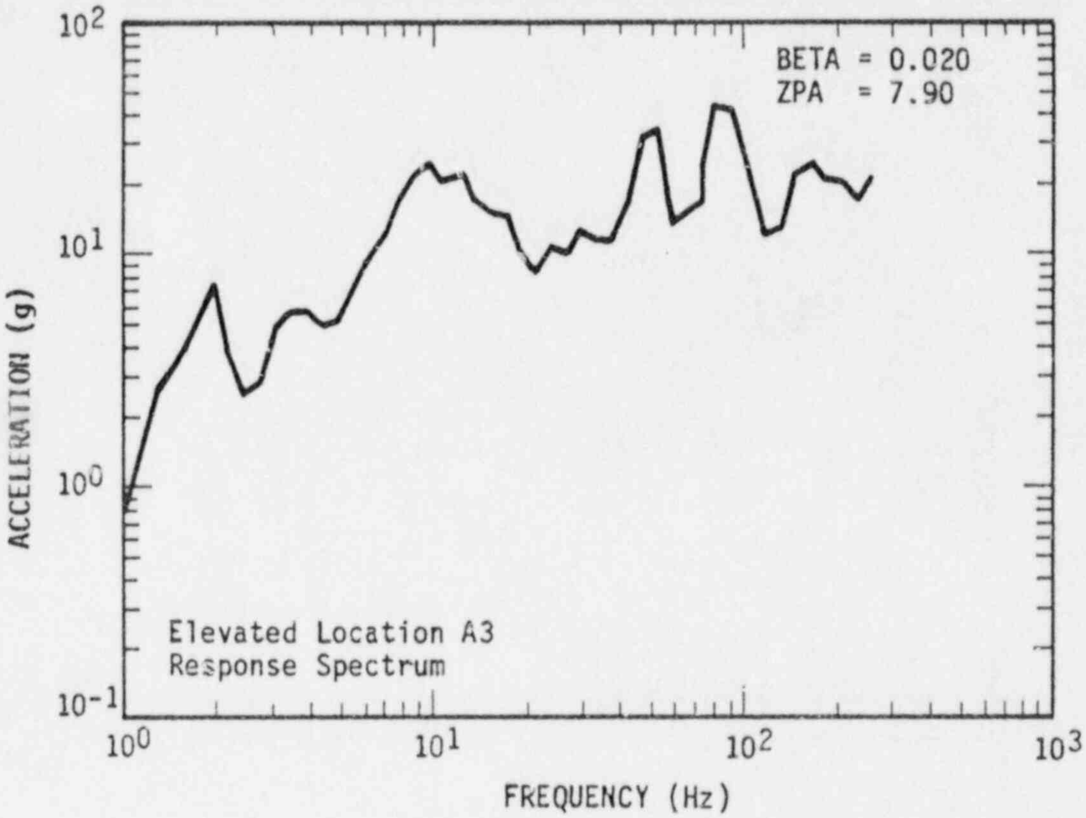


Figure 30. Location A3 transfer function for 72" Mockup Panel



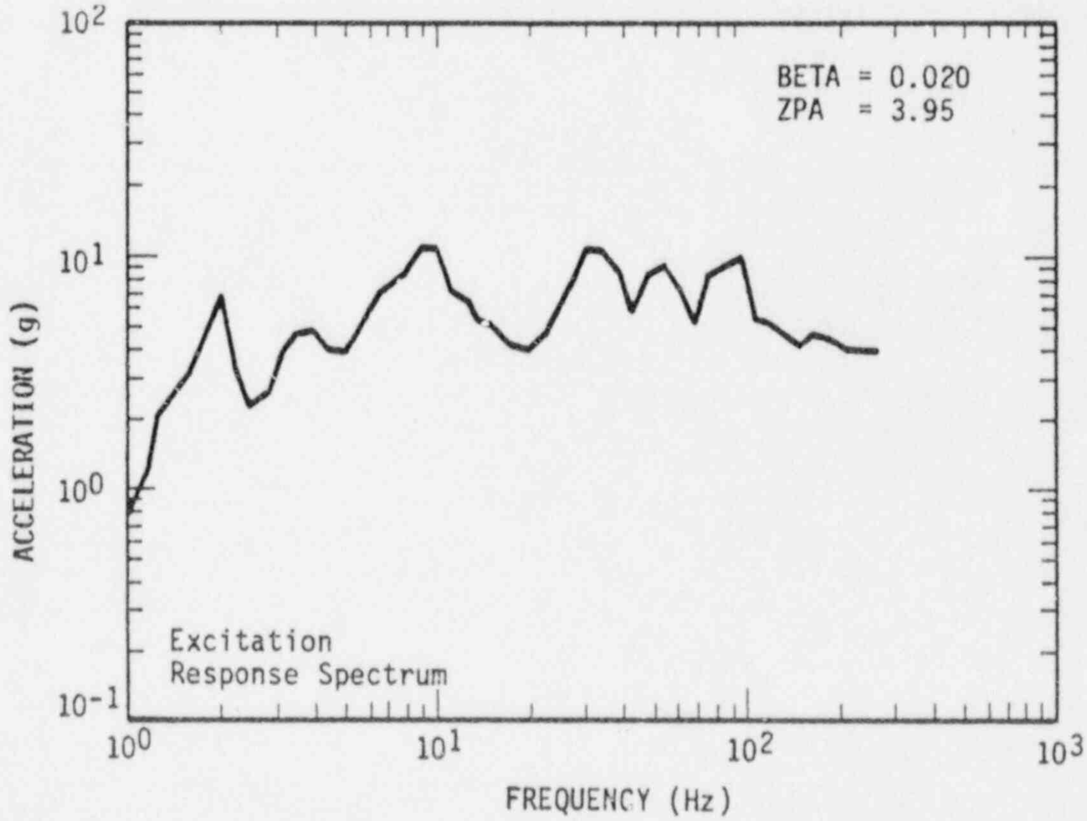


Figure 31. Qualification data for 48" Mockup Panel

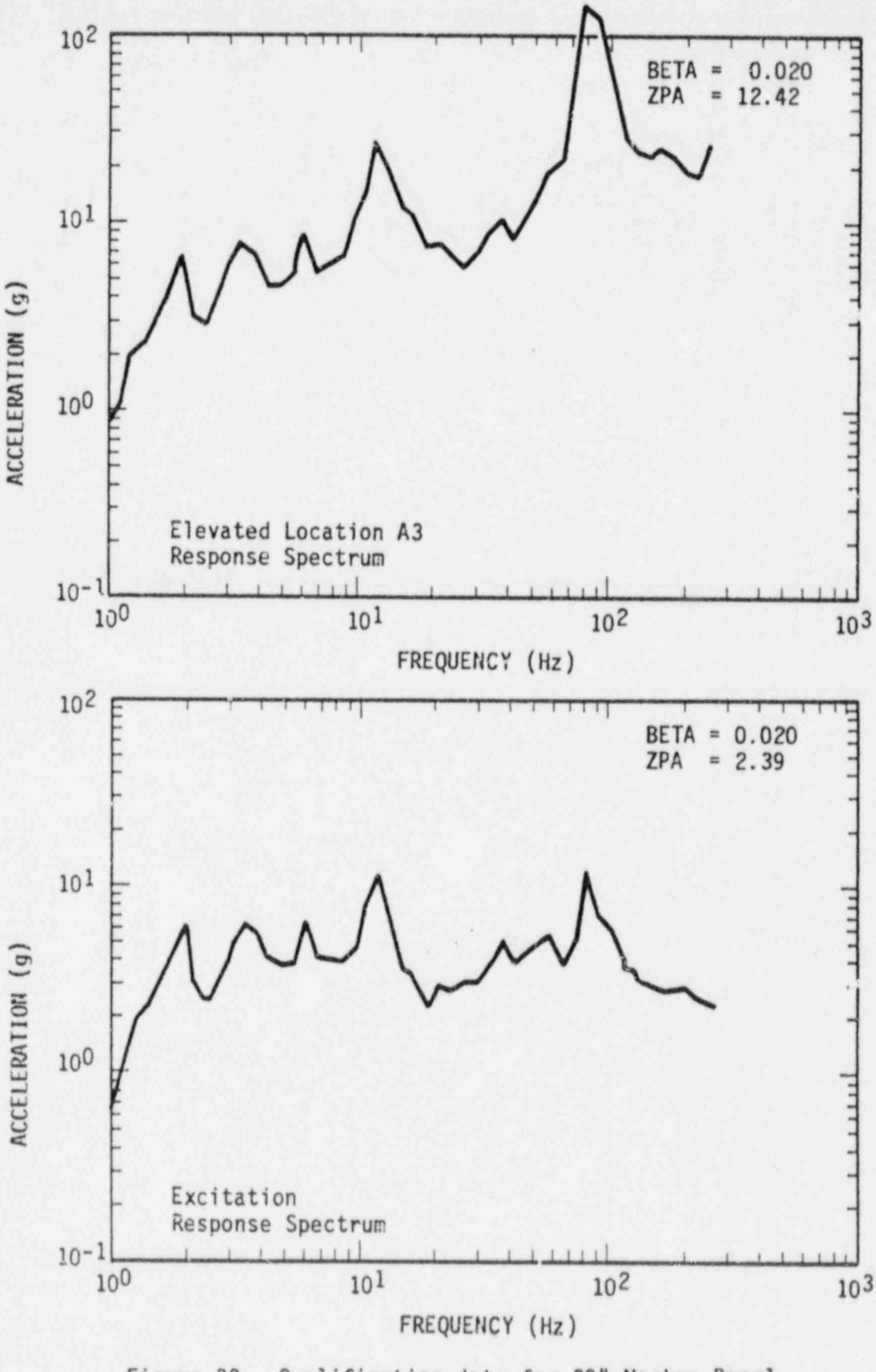
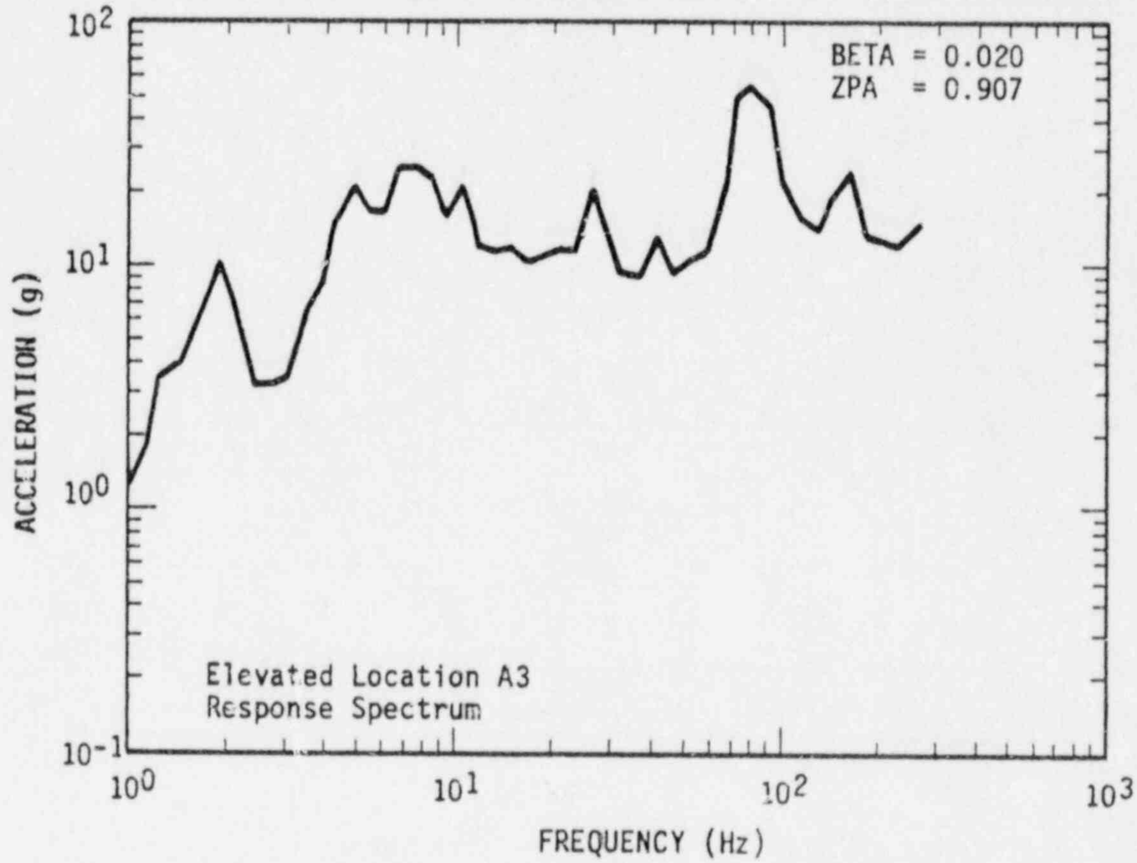


Figure 32. Qualification data for 30" Mockup Panel



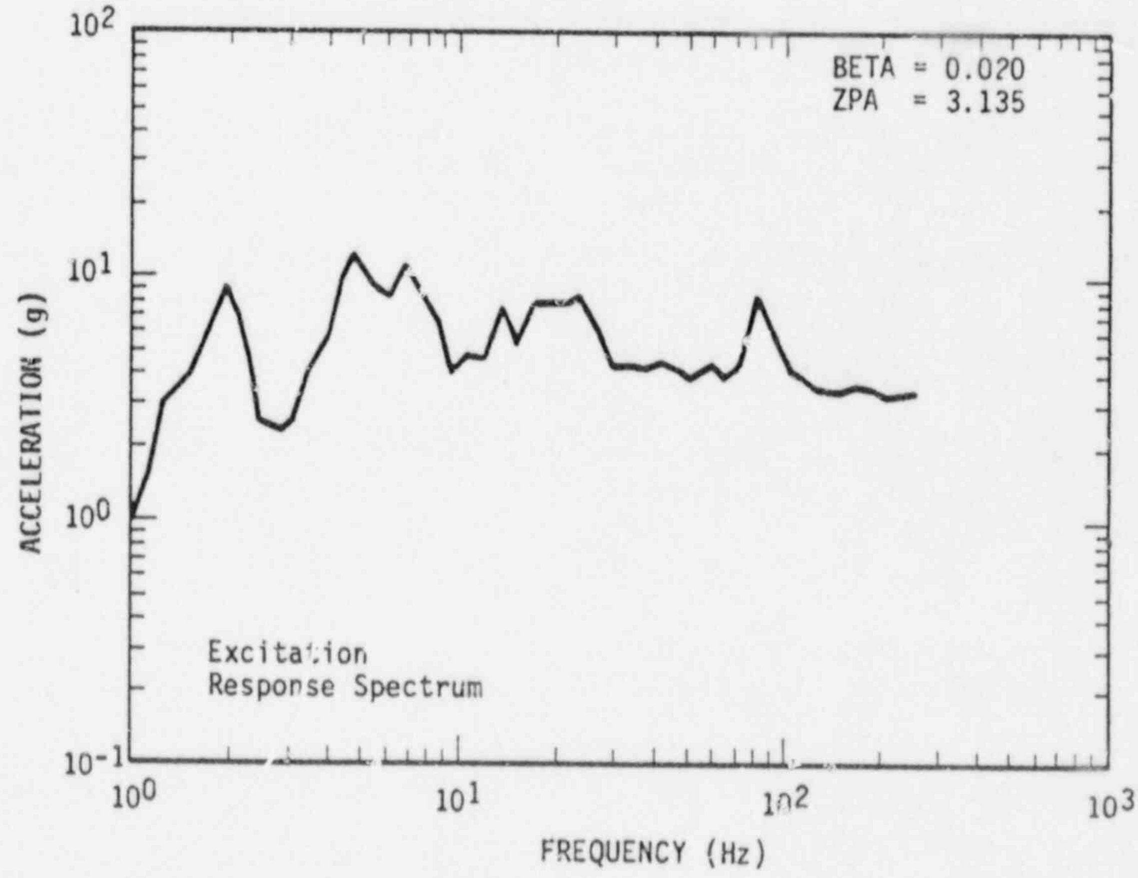


Figure 33. Qualification data for 72" Mockup Panel

In view of all of the above experience data, two pertinent questions now are: (1) Given that the 48" panel was previously qualified with instruments installed, can qualification for this panel also be claimed for some level of the spectrum shown in Figure 31; furthermore, (2) Can qualification of the other two panels be established from the existing data for the case of identical instruments (devices) installed on those panels?

First, consider qualification of the [illegible] panel to the spectrum shown in Figure 31. This is a problem similar to that described in Paragraph 4.3.1. However, the critical bandwidth must include up to about three modes for this case (see Figure 28), i.e., from about 21 Hz to 51 Hz. Not only are the three modes almost equally as prominent, but the spectrum in Figure 31 also includes energy throughout this range, as indicated by amplification of the ZPA level. From Figure 26a, it can be seen that the $R_{x1}(f)$ response spectrum dips to as low as about 2.4 g in the Δf_{cc} range. The $R_{x2}(f)$ spectrum of Figure 31 is as high as about 11 g in this range (for 2% damping). Thus, the $R_{x2}(f)$ spectrum of Figure 31 must be reduced overall by a factor of 2.4/11 = 0.22 before the panel with instruments can be considered qualified to it. In doing this, note that the new ZPA is 3.95 (2.4/11) = 0.86 g, which is indeed less than that for $R_{x1}(f)$ in Figure 26a. As a matter of interest, note also that a factor of 0.22 times the A3 elevated spectrum of Figure 31 becomes essentially less than the A3 elevated spectrum of Figure 27. A retrace of the two excitation spectra is shown in Figure 3[illegible], where it can be seen that some part of $R_{x2}(f)$ still exceeds $R_{x1}(f)$. However, this occurs outside the range Δf_{cc}. Furthermore, by inspection, it is estimated from the critical transfer function in Figure 28 that Step 5 of Paragraph 4.3.1 is satisfied. Hence, the 48" panel with instruments installed is also qualified to $R_{x2}(f)$.

[illegible] consider qualification of the 72" and 30" panels to $R_{x1}(f)$ (i.e., Figure 2[illegible]). By examining Figures 28-30, for this the composite [illegible] frequency bandwidth is judged to extend from about 11 Hz to 90 Hz [illegible] multimode behavior occurs, and energy is present [illegible] For each panel, the respective spectra must be reduced [illegible] appropriate factor so that each is less than $R_{x1}(f)$ in the

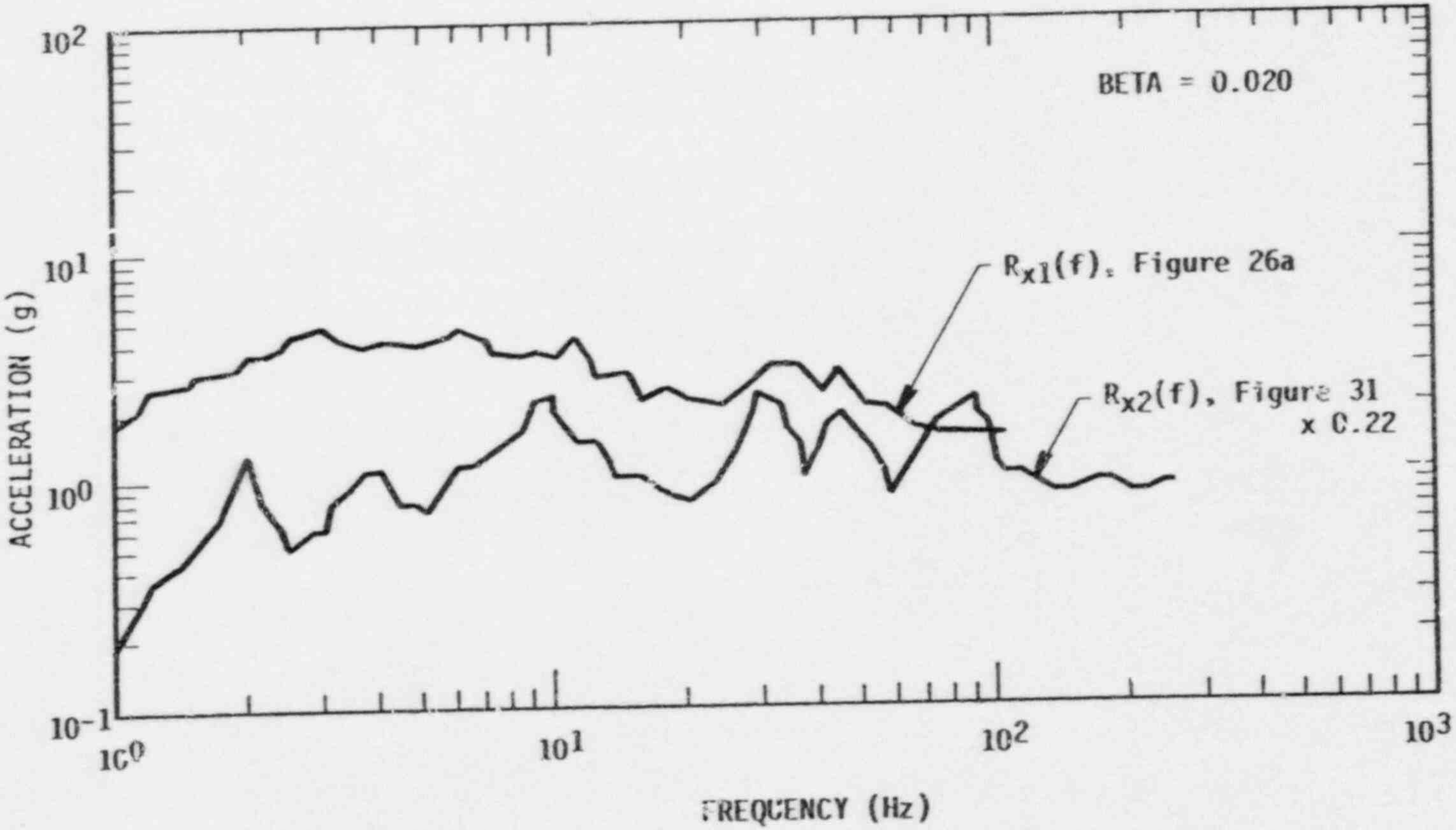


Figure 34. Two qualification spectra for the 48" Local Panel

range Δf_{cc} of 11 Hz to 90 Hz, and the respective ZPAs must be less than that for $R_{x1}(f)$ (i.e., 1.51 g). By examining the spectra, the following reduction factors must be used: within bandwidth Δf_{cc}, reduction = low point of $R_{x1}(f)$/high point of $R_{x2}(f)$.

30" Panel (Figure 32) reduced by 1.51/12 = 0.13
72" Panel (Figure 33) reduced by 1.51/8.5 = 0.18

By inspection, it is estimated that Step 5 of Paragraph 4.3.1 is satisfied, so that these panels are now qualified to $R_{x1}(f)$ and their respective reduced spectra, when they have the actual devices installed.

8. DISCUSSION

The principles outlined herein should provide a significant step forward in extending the rather broad guidelines outlined in the revised IEEE 344 [2] and currently developing ASME Standard [10]. They also are useful for comparing with methods used by the Seismic Qualification Utilities Group (SQUG) for qualifying equipment in existing plants. The former guidelines lack sufficient detail to be workable, while the latter methods are viewed by some to lack sufficient rigor for use in new plants. Thus, the methods herein are intended to show a path whereby a compromise between the two may be pursued. They are further intended to provide detailed procedures for use by anyone who has available appropriate experience data.

It is apparent that the major difference between qualification by experience and more conventional methods lies in significantly greater use of what may be called "justifiable judgment". The methods developed herein are intended to be a basis for justification of judgments that typically will be made in lieu of detailed analyses or tests to carry out various qualification scenarios. There are several elements that form the essence of this basis. It is asserted that two of the three forms of similarity usually must be satisfied for a valid application. Furthermore, the two types of similarity must correspond within a critical frequency range in which the considered equipment is most susceptible to malfunction. Outside this bandwidth, the similarity requirements are much less stringent, but of course not unlimited. By using whatever means possible, the qualification engineer's job must be to predict what an equipment item's dynamic characteristics are, especially within the critical frequency band; and from that, show that the item's behavior would be essentially the same as other equipment in a data base whose dynamic characteristics are similar. By concentrating on behavior only within the critical frequency band, much more freedom is allowed in the qualification.

A major concern lies in the detail to which physical similarity must be established. In effect, this means to what detail the critical transfer function must be established. Picking the critical location on a primary structure requires the assumption of the most likely form of malfunction. But even beyond this, what constitutes sufficient data for the transfer function at this location? It is our judgment that resonance search data of the type obtained from typical exploratory tests is quite adequate for this important step. If no such data is available, the transfer function must be estimated from comparisons of stiffness and mass properties (i.e., modal participation characteristics), and damping. From the examples given herein, it is obvious that the more generic the initial constituent response spectra, the broader the critical bandwidth Δf_{cc} can be made and, correspondingly, the less important is the accuracy of the estimate on the equipment critical transfer function. Conversely, the less generic (i.e., more site specific) the initial data, the narrower will be Δf_{cc}, and the more accurate the critical transfer function must be established. Thus, the most appropriate approach to a given qualification scenario will depend on the nature of the data and equipment characteristics which form the data base.

The examples developed for the simple primary/secondary system are useful to demonstrate and validate the similarity principles under those conditions assumed for malfunction. Extreme care should be exercised in generalizing the results to other conditions. In particular, for all cases, peak acceleration was assumed to be the source of malfunction. Even for the simple system, other parameters such as peak displacement, peak stress (relative displacement), or other parameters may be appropriate. Furthermore, the use of a time history method includes inherent variations in results due to statistical properties of specific time histories. However, inclusion of any potential modal interaction was desired, and could only be done by further approximation if response spectrum combination methods were considered. At the same time, a point must again be made that any qualification by experience data inherently requires assumption of the most likely form of malfunction, and a location in the primary structure whose response is related to that malfunction. Obviously, the qualification is valid only within the accuracy of those assumptions. An equally significant result from these examples has been that some modal interaction correction is necessary even for random waveforms when relatively narrowband components are present. Thus, composite spectra generated from especially narrow floor-level biaxial test spectra may still need to be reduced by the 0.7 factor. Furthermore, although no multiaxis correction has been emphasized herein, it should be understood that a 0.7 factor is also appropriate for data generated under single-axis conditions.

The adequacy of maximum spectral amplification factor for approximate determination of waveform similarity needs to be explored further. However, significant support for the use of this parameter has been developed in Appendix A. This ratio is especially easy to determine from given response spectra; therefore, more knowledge of its overall affect on the qualification problem would be useful to allow more freedom in its use. Waveform similarity exists for spectra whose corresponding data fall into similar regions of a curve such as given in Figure A-9. It appears that the requirement that similar ratios exist for composite and constituent spectra constitutes a major difference between the methodology developed herein, and those previously published.

The outlined spectrum extension approach is essentially new. Typically, in the past, qualification test runs were repeated where only a very slight undershoot of a RRS by a TRS occurred. It is believed that this approach will be most important in a variety of scenarios for extending use of already existing data, even beyond those mentioned in this report. In effect, the approach represents the inverse of qualification by similarity. That is, if one is convinced that a composite spectrum can be developed from a group of different individual spectra, then one must also accept the inverse as being valid. Both concepts rely on some prior knowledge about the critical transfer functions of the equipment involved.

The principles outlined herein rely heavily on the establishment of a critical transfer function and its use to demonstrate physical similarity. Inherently, the use of low-input level transfer functions, such as typically measured during resonance search, are considered appropriate.

However, should significant nonlinearity be suspected in a specific case, then additional measures could be implemented to develop quasi-linear transfer functions. One approach would be to develop the data from fast Fourier transforms of the time histories of both excitation and response locations during the actual test events, if such data were available. However, in general, it is doubtful that any accuracy gained from such an approach would warrant the effort. In fact, virtually all known analytical qualification schemes are based on such linearity in any event.

Examples presented herein tend to support two important assertions; (1) the critical transfer function can be determined on a primary structure and, (2) the 0.7 factor is conservatively adequate for allowing for modal interaction. Nevertheless, care again must be exercised in generalizing these assertions to other type applications. The data herein provides more information where, heretofore, little or no information existed. On the other hand, it is conceivable that on certain types of secondary devices, the critical transfer function may have to be defined directly on the secondary device, rather than on the primary structure. That is, the natural frequencies of the devices and their inherent sensitivity may be significantly different from that of the primary structure. For any equipment in which this type of behavior occurs, the methodology described herein is still applicable. However, the critical transfer function must be defined at the location whose response is most directly related to the failure of the equipment. Herein, emphasis has been placed on transfer functions for the primary structure, since this approach appears to be adequate for many types of equipment, and also allows use of most existing data acquired during previous qualifications.

Finally, in view of the principles and evidence presented in this report, it is appropriate to ask what specific information is most important to include in a report of a given qualification scenario. Some appropriate information is as follows:

(1) Identification of the type of equipment which forms a data base and general physical characteristics of each item. (Note that

with the methodology developed herein, only a few select items are required rather than many whose initial qualifications were not very severe. Furthermore, exact identifying information may be kept confidential, but must be traceable.)

(2) Identification of the most probable form of malfunction for the equipment.

(3) Evidence of a critical transfer function in some appropriate form for each item in the data base. Include an identification of Δf_{ci}, peak response magnitude, and critical location for each item. An alternative for peak response magnitude can be evidence of modal participation at the critical location and damping of the equipment.

(4) Evidence of a critical transfer function in some appropriate form for any candidate equipment item, and a statement about its most probable form of malfunction. Include identification of Δf_{ci}, peak response magnitude, and critical location. Again, evidence of modal participation and damping can replace measured peak magnitude values.

(5) An overlapping graph including each constituent spectrum identified with its corresponding data base equipment item, and any composite spectrum used in the qualification. Include an identification of Δf_{cc}.

(6) An assertion as to how any candidate item satisfies procedures in this report (and, thereby, in Reference 2), as a basis for its qualification.

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10. ACKNOWLEDGMENTS

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G. L. Thinnes	Idaho National Engineering Laboratories (INEL Project Monitor)
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Mike Skreiner	NUTEC
G. E. Sliter	Electric Power Research Institute
K. Merz	ANCO Engineers
J. D. Stevenson	Stevenson and Associates

APPENDIX A
SIMILARITY OF EXCITATION WAVEFORMS

APPENDIX A

SIMILARITY OF EXCITATION WAVEFORMS

A1. INTRODUCTION

In the past, various waveforms have been used to represent seismic excitation for equipment qualifications. Documentation of a qualification has usually been given in terms of the response spectrum computed from the given test waveform, rather than a time history of the waveform itself. To be used for qualification by experience, such constituent response spectra may be formed into a composite. Since the nature of a given waveform can have a significant bearing on the outcome of a qualification, consideration must be given to the similarity of various corresponding waveforms to assure compatibility of the composite spectrum with the constituent spectra. In other words, a waveform which corresponds to the composite spectrum must be similar to the waveforms which correspond to the respective constituent spectra. Therefore, this appendix presents a method whereby similarity of various excitation waveforms can be established by an approximate method.

Generally, several parameters are necessary to characterize the dynamic properties of a waveform which describe its frequency content, stationarity, and amplitude distribution. For typical signals (including sine dwells, sine beats and random signals of various bandwidths and duration), parameters such as power spectral density, probability density, and Peak/RMS ratios can be used to characterize the signals and the response of linear systems to which they may be applied [A1].[a] However, the response spectrum, rather than any of the above, is the typical parameter available from qualification reports. It is possible to estimate the former parameters which would correspond to a given response spectrum, but the methods are relatively elaborate [A2], and the accuracy required to show waveform similarity probably does not warrant their use. Therefore, an approximate approach to demonstrate waveform similarity will be based on

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a. References are given at the end of this appendix.

the ratio of the maximum spectral response of a damped single degree-of-freedom oscillator to the peak acceleration (ZPA) for the waveform used to excite the oscillator (i.e., maximum output/peak input); a ratio that can readily be obtained directly from the shape of the response spectrum for a given waveform. Comparisons with Peak/RMS ratios for the same waveforms also will be included to relate the development more directly with stationary random process concepts.

The maximum output/peak input ratio for an oscillator, which was defined as $R_x^*(f)/ZPA$ in Section 3.1.2 of the main report, also can be called the maximum amplification factor. The sensitivity of this factor for a single degree-of-freedom oscillator excited by several typical waveforms has been recognized in the past [A3], and is shown for convenience in Figure A-1. It will be shown in this appendix that this amplification factor also can be related to the shape of the excitation response spectrum in terms of the maximum spectral value, the bandwidth, and the center frequency of the amplified region (i.e., where the spectral values are greater than the ZPA). Similarity of this factor between various response spectra will be shown to be sufficient to establish corresponding waveform similarity. Hence, by inspection of the test response spectra generated during a qualification program, it will be possible to develop the ratios required to show waveform similarity for the corresponding excitations. Subsequently, the same approach can be used to assure waveform similarity for any further developed composite spectrum. This will further assure that the generated composite spectrum can be matched by an appropriate time history, without having to produce the actual time history.

From Figure A-1, it is obvious that the maximum amplification factor for a given waveform depends on both the frequency and the damping of the oscillator. Furthermore, it is obvious that the bandwidth and center frequency for the excitation will influence the results. Therefore, herein it will be understood that the maximum amplification factor will be

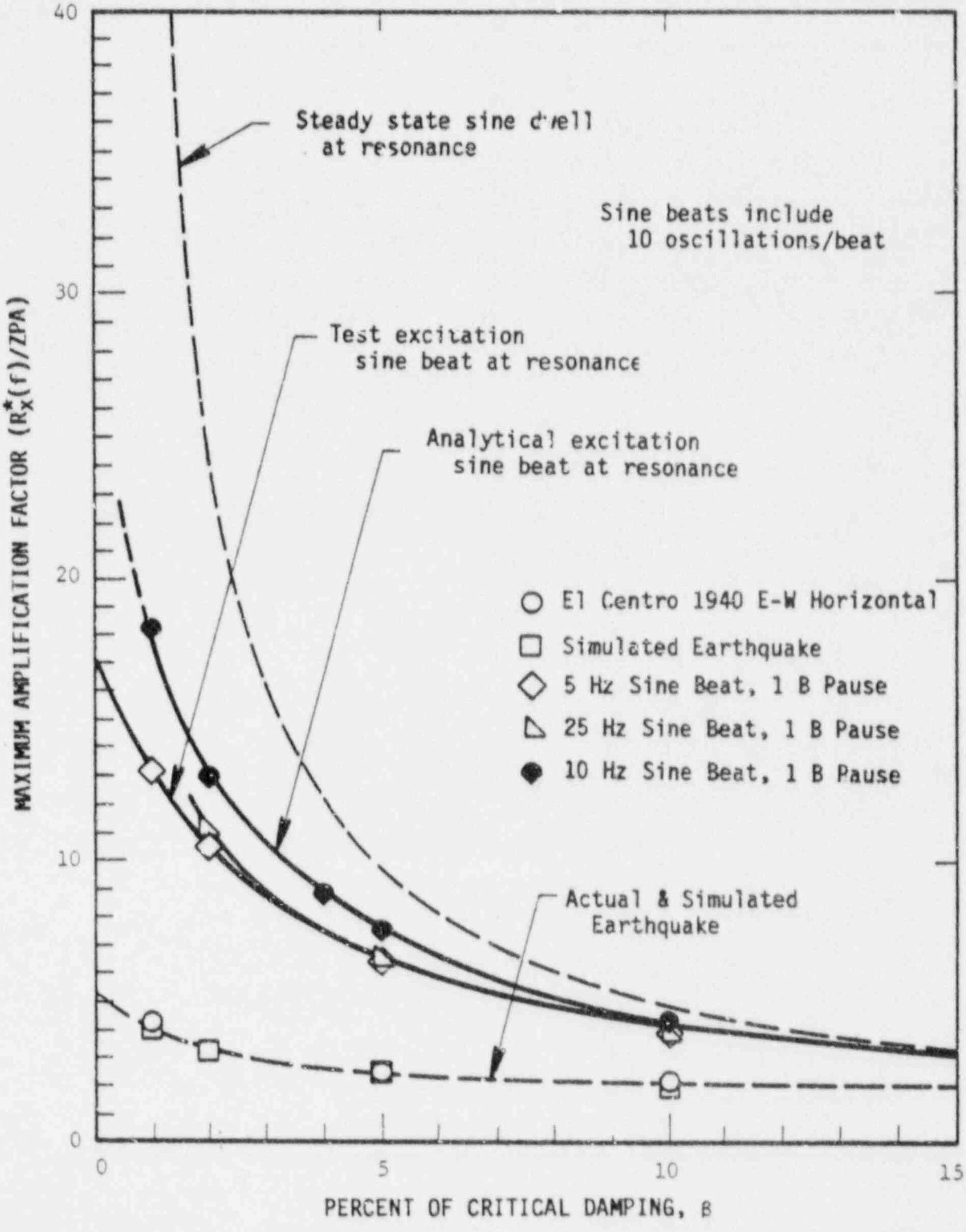


Figure A-1. Maximum spectral amplification factors for a SDOF system under various excitation conditions constant for a spectrum which is flat in the frequency band of concern, some average value for one which is sloped, and some weighted value for complex spectra that include multiple peaks. Hence, the analysis herein begins first with simple spectra that represent flat random energy excitation in a single frequency band of specified width. This allows a better initial grasp of the physical significance and importance of waveform similarity. All analyses will be based on 5% damping for the various spectra, a value representative of equipment. Subsequently, further discussion will be included to indicate the effects of more complex types of response spectra, and other values of damping.

For this analysis, it is assumed that the duration of a time history which corresponds to a composite spectrum is similar in length to those of the constituent spectra. In addition, it is assumed that energy in the various amplified regions is present during the entire strong motion portion of the signal. This concept of stationarity is consistent with the requirements for random motion testing defined in IEEE-344 [A4]. Only Gaussian random motion is considered in this analysis, since the data for other types of motion (i.e., sinedwells or sinebeats) are not often presented in terms of a response spectrum. Determination of similarity of these types of waveforms is easier to accomplish directly, rather than using the response spectrum or other parameters mentioned above.

A2. SIMPLE FLAT RESPONSE SPECTRA

For this part of the analysis, maximum amplification factors are studied for various simple response spectra that are essentially flat in the amplified region of a single frequency band. Corresponding time histories are developed for various spectra having different single bandwidths and center frequencies. The data are ultimately plotted to show variation of maximum amplification factor (i.e., labeled as Peak/ZPA) as a function of bandwidth and center frequency. The corresponding time histories are used to determine ZPA/RMS ratios for comparison. Up to five corresponding time histories are developed for each response spectrum to indicate statistical influences on the results.

The procedure utilized to generate a time history to match a specified response spectrum is an adaptation of that described in Reference [A5]. It is an iterative procedure in which the time history is developed for a weighted linear sum of nonstationary narrowband pseudorandom noise signals. The nonstationarity is associated with the envelope (5 second buildup, 15 second hold, and 10 second decay) used to represent the earthquake signal. For this program, a series of 99 narrowband pseudorandom noise signals were generated at even frequency intervals from 1.0 to 50.0 Hz, i.e., a bandwidth of 0.5 Hz each. An initial guess of the required weighting factors used in the summation was made and the time history generated. The response spectrum for this time history was then calculated and compared to the one required. Adjustments were then made to the weighting factor for each bandwidth, and the procedure repeated until an acceptable match was achieved. At this point, the RMS value for both the entire time history and the strong motion portion (15 second hold) were calculated. In addition, the time history was plotted along with the corresponding response spectrum. Each time history was generated with a sample rate of 512 samples/second over the duration of the signal.

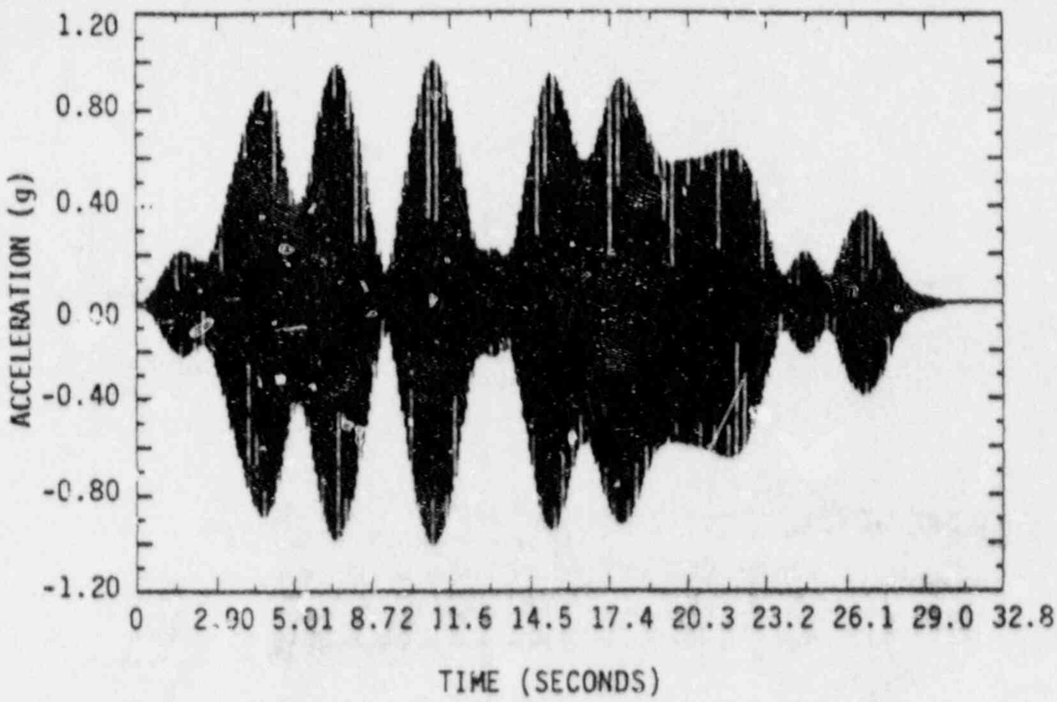
Using the signal generation procedure described above, it was possible to develop spectrally-compatible time histories having energies only in a preselected bandwidth, which could be related to a given spectrum. This was done by forcing to zero all weighting factors for frequency bands outside the preselected bandwidth. This approach is consistent with the requirements of Reference [A4], which states that energy above the required response spectrum ZPA cutoff frequency should not be included in the time history. However, even with this capability to limit the bandwidth of excitation, it is not physically possible to generate a time history which produced a response spectrum with sharp break-over points. This has to do with the nature of the response spectrum calculation and bleed-over of values. Therefore, the values for bandwidth presented represent the energy bandwidth as defined above, which corresponds to about 0.8 times the calculated maximum response spectrum values.

A2.1 Typical Results

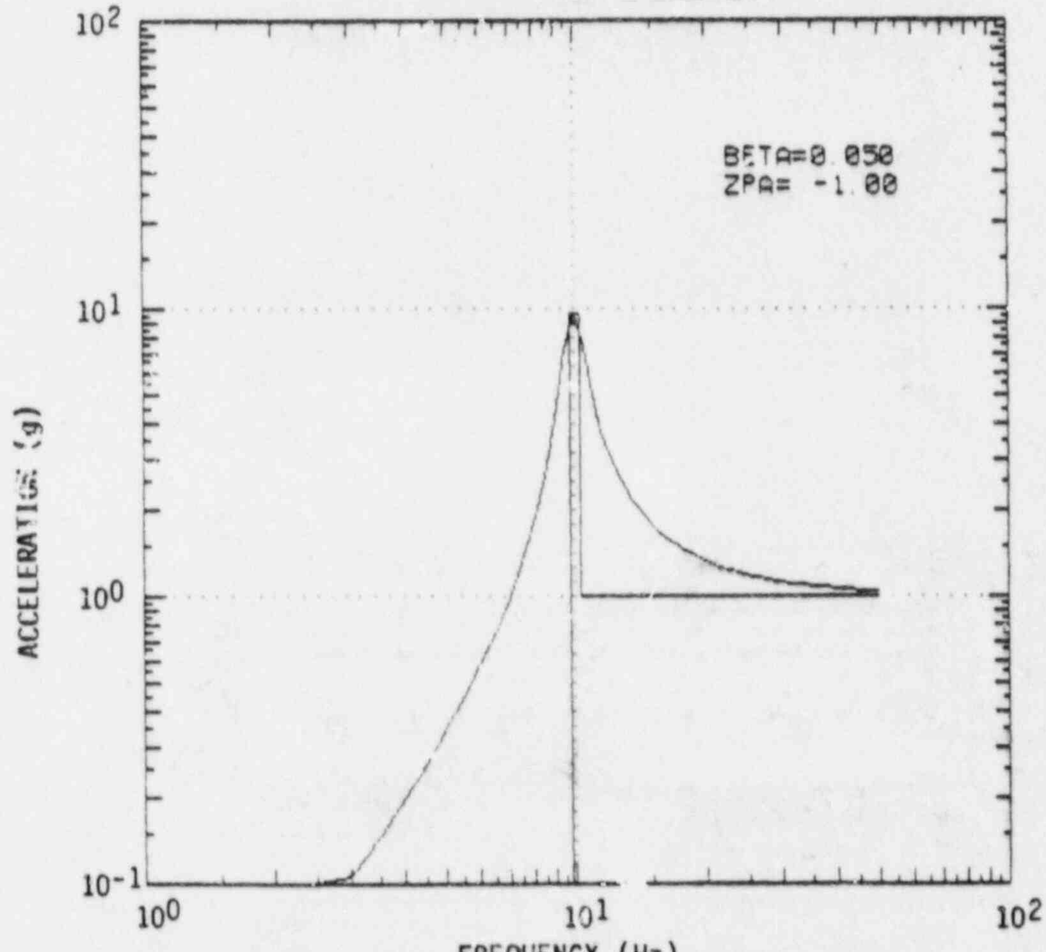
Spectrally-compatible time histories were developed and studied for response spectra having center frequencies of 5, 10, and 20 Hz, with bandwidths varying from 0.5 Hz to a maximum, where the lower limit was set at 0.75 Hz and the upper limit was two times the center frequency, minus 0.75 Hz. As noted previously the damping was set at 5%. Figures A-2 through A-4 show several examples of spectra and their associated time histories. In the lower part of each figure, the specified frequency bandwidth is shown by a rectangular curve, along with a response spectrum computed from the time history given in the upper part of the figure. The indicated curves allowed a determination of the 0.8 factor mentioned previously.

The next step of analysis included plotting of results from one set of time history data, as shown in Figures A-5 and A-6. Each point on these curves results from data taken from Figures A-2 through A-4 and other similar plots. The maximum spectral amplification factors are labeled as $R_x^*(f)/ZPA$. Bandwidths and center frequencies correspond to the rectangular curves. Finally, RMS values are calculated from the appropriate time history during the strong motion. Thus, for a given bandwidth and center frequency for a specified response spectrum, both the $R_x^*(f)/ZPA$ and ZPA/RMS ratios can be compared for corresponding spectra.

To obtain some information on the statistical variations associated with the analysis, spectrally compatible transient random time histories were generated from five sets of statistically independent, narrowband pseudorandom signals. The data was tabulated from each of these time histories, as described above, were analyzed statistically, and then plotted as shown in Figures A-7 and A-8. Although the maximum amplification factor, given in Figure A-7 has some significant scatter, there are several observations that can be made:

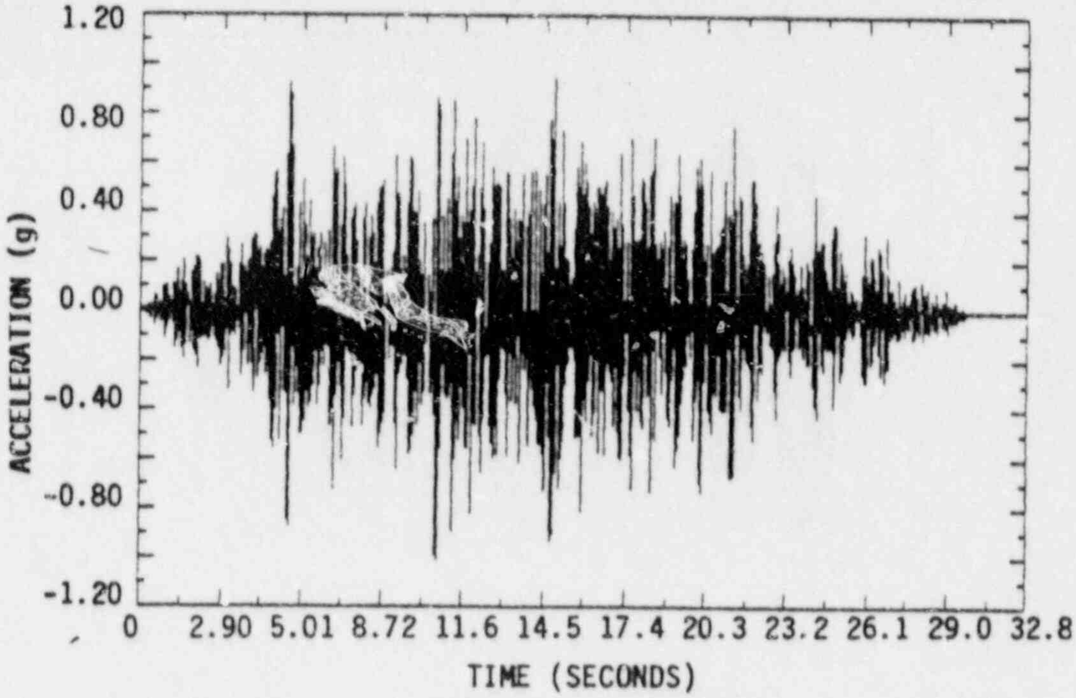


a) Time history

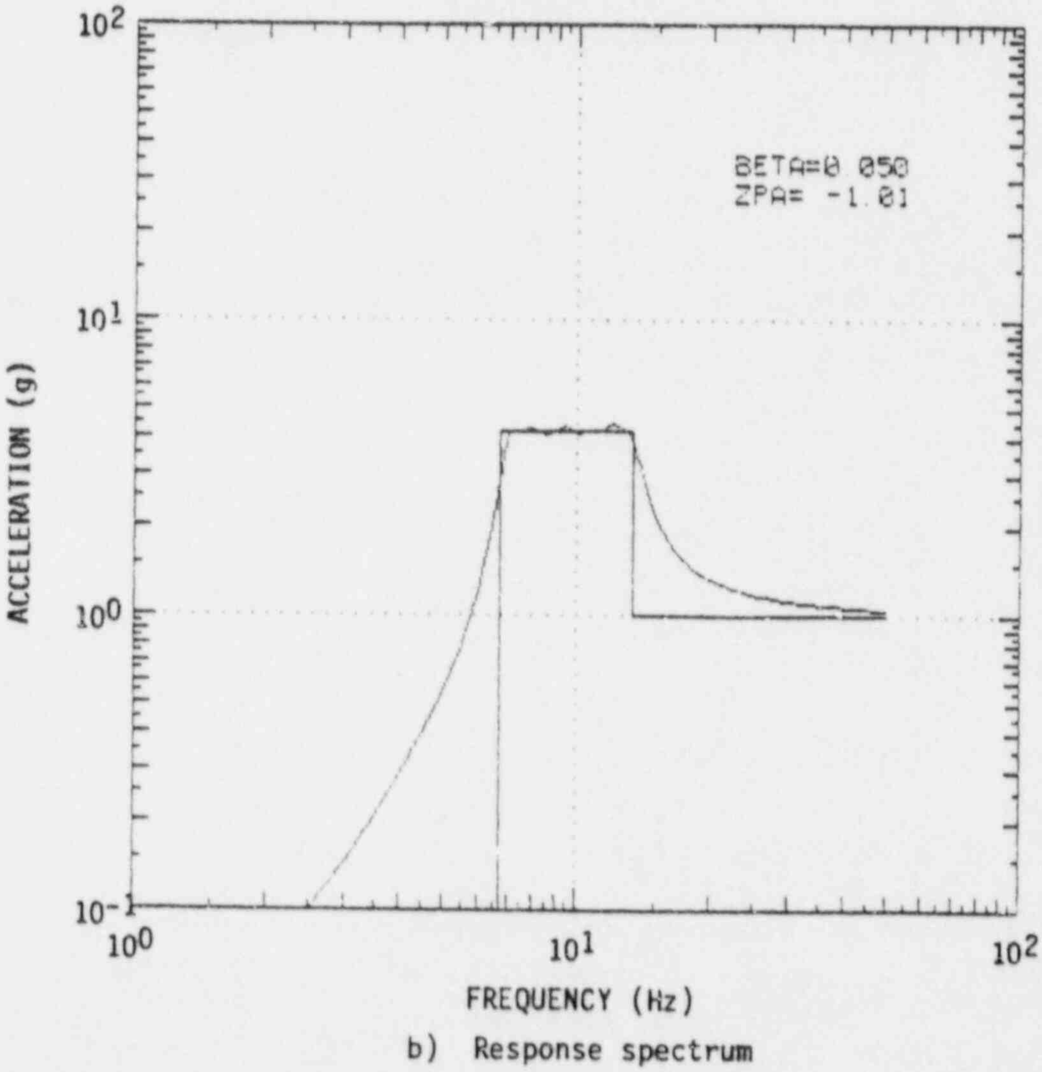


b) Response spectrum

Figure A-5. 10 Hz center frequency with a 0.5 Hz bandwidth

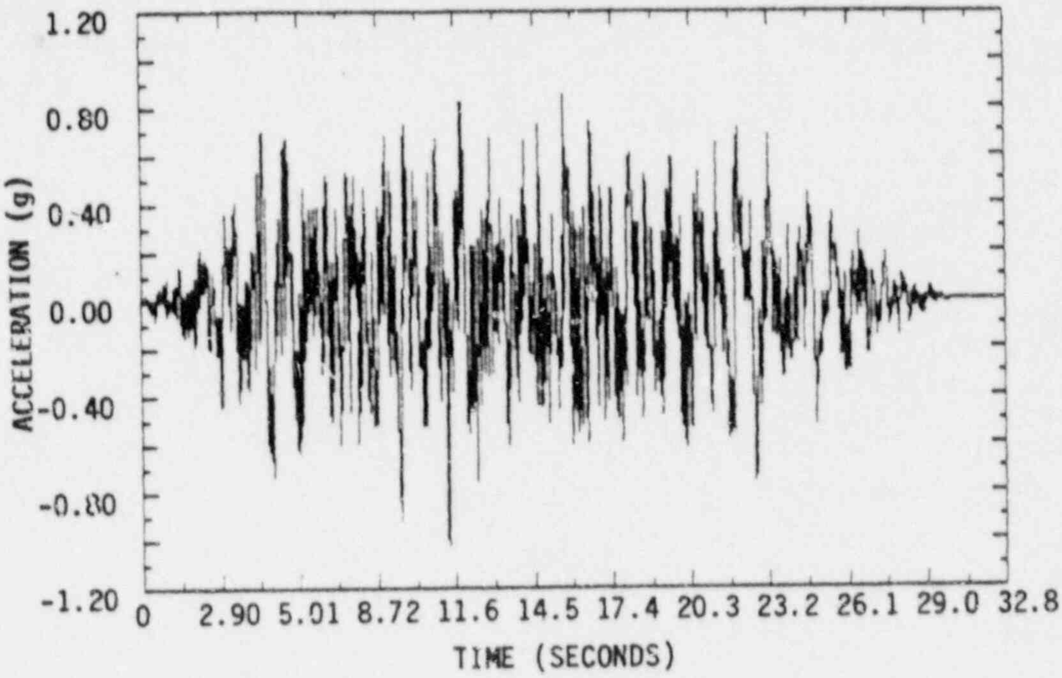


a) Time history

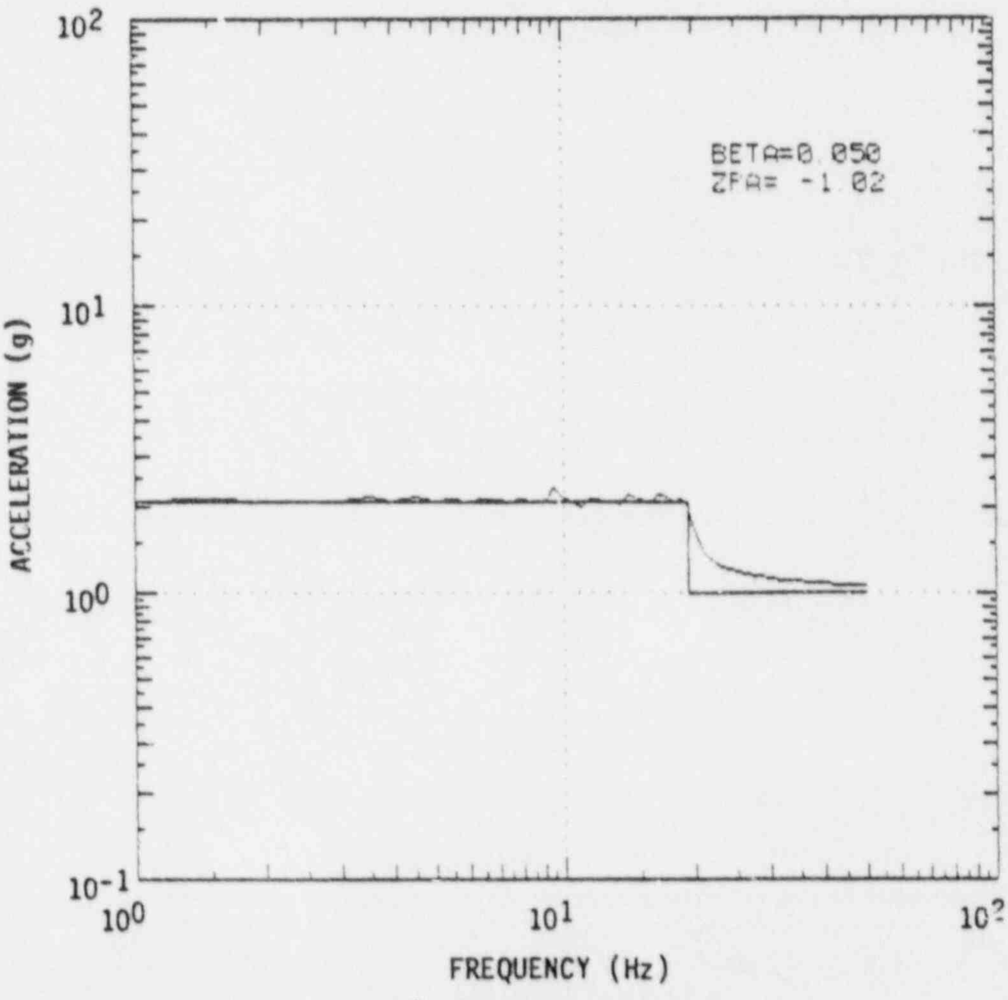


b) Response spectrum

Figure A-3. 10 Hz center frequency with a 6.5 Hz bandwidth



a) Time history



b) Response spectrum

Figure A-4. 10 Hz center frequency with a 18.5 Hz bandwidth

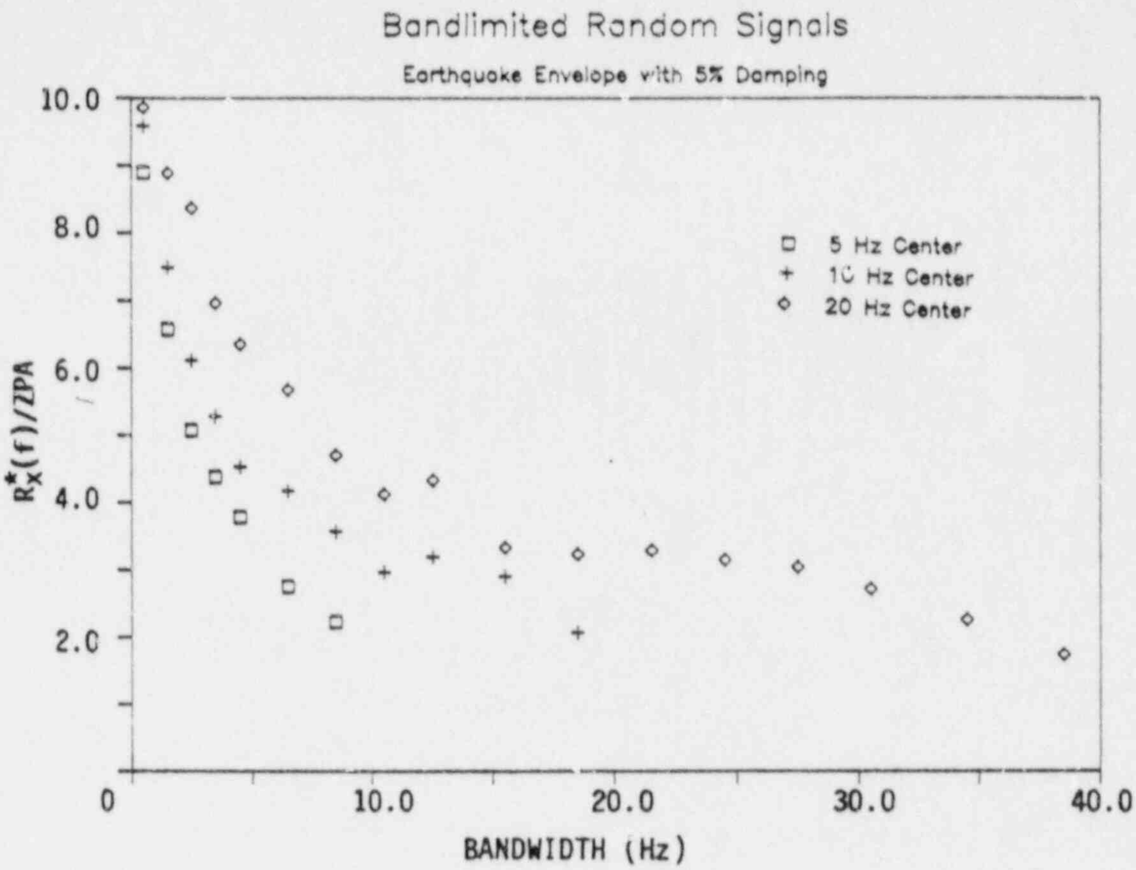


Figure A-5. Time history set no. 1 extended data for $R_x^*(f)$/ZPA ratio

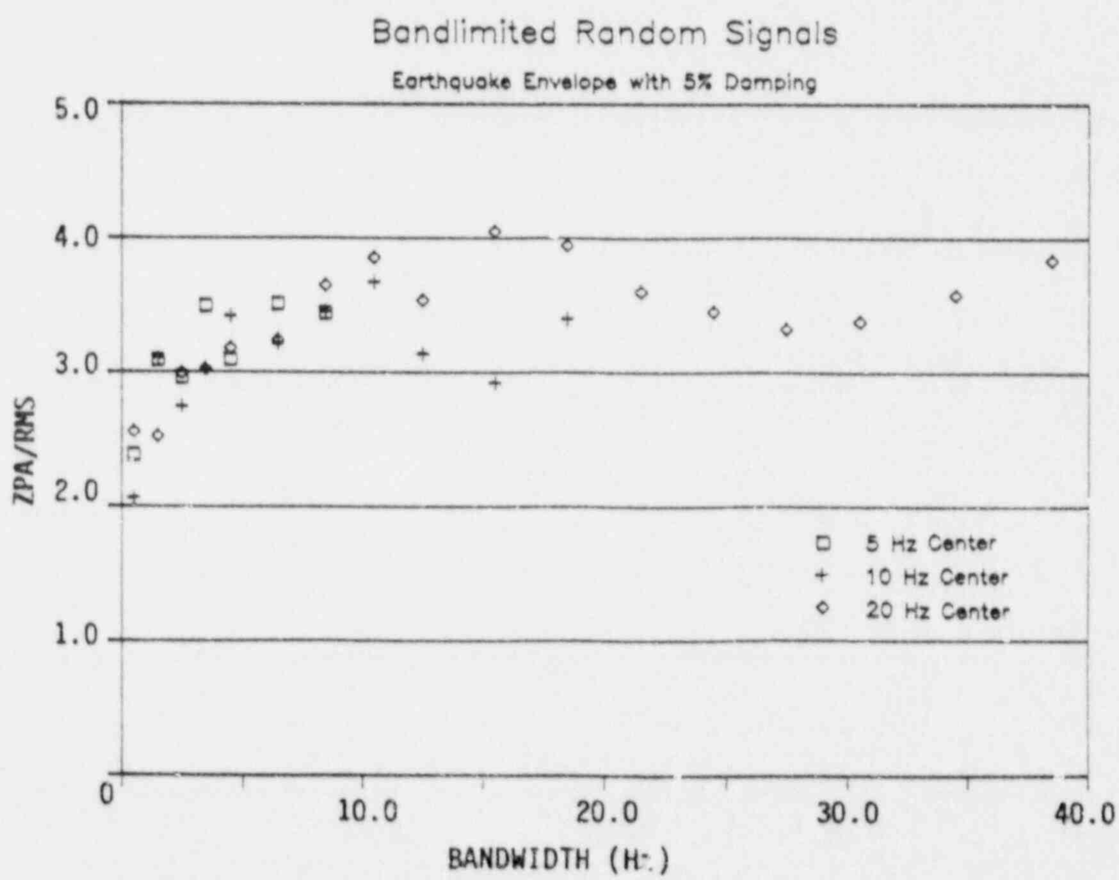


Figure A-6. Time history set no. 1 extended data for ZPA/RMS ratio

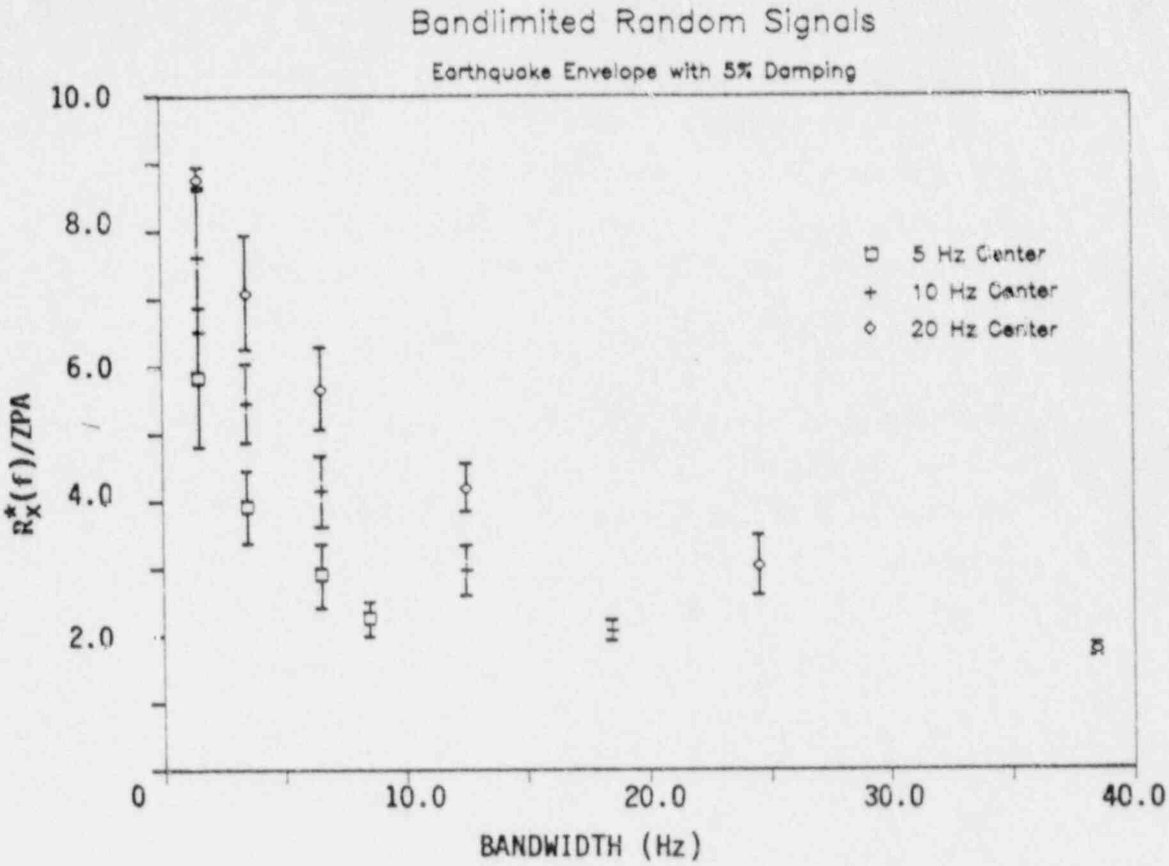


Figure A-7. Mean and 2-sigma bands for $R_x^*(f)/ZPA$ ratio

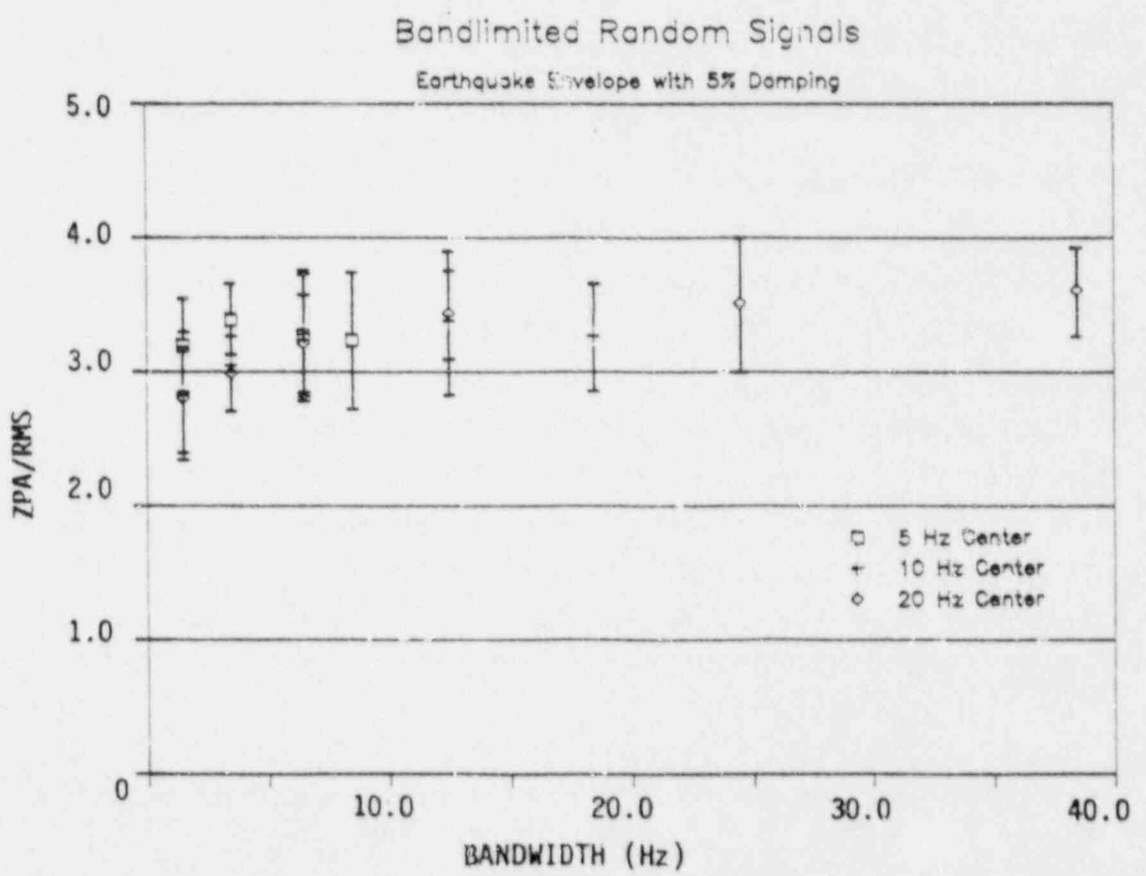


Figure A-8. Mean and 2-sigma bands for ZPA/RMS ratio

(1) As the bandwidth approaches zero (i.e., sinusoidal excitation) the ratio approaches a value of $1/(2\beta)$, the response of a damped single degree-of-freedom system to steady-state sinusoidal excitation. In this case, the response spectrum reduces to the response of a damped single degree-of-freedom system at the center frequency.

(2) Even for a relatively short duration (15 seconds) of the strong motion portion of the signal, the system will develop to its full resonance response. The number of cycles for buildup of resonance response from rest under sinusoidal excitation has been shown to be approximately equal to [A6]:

$$\text{cycles} = \frac{-\ln[1-R(t)]}{2\pi\beta} \tag{A-1}$$

where $R(t)$ is the required buildup level, i.e. $R(t) = 0.95$ for 95% of the steady-state response. For the three center frequencies and 5% damping utilized, the system can be shown to build up to its full response in the 15 second strong motion portion of the signal.

(3) At a given bandwidth, the maximum amplification factor increases with increasing center frequencies. There is a trend to the data in each group and, therefore, it may be possible to develop some analytical expression to match the data.

(4) The maximum amplification factor seems to approach an asymptote. It is felt that the asymptote can be related to the response spectrum for classical shock pulses and is a function of the center frequency and damping of the system. In a limited literature search, it was not possible to obtain any information on what this value should be. However, in no case should the value go below 1.0.

Figure A-8 gives the corresponding ZPA/RMS ratio. For a stationary random signal with Gaussian distribution, one would expect the value to be around 3.0. Since the signal in question is transient, then the value would be expected to be greater than 3.0, as is evident. There is some decrease for the lower bandwidths, but the change occurs only below about 3 Hz. As the bandwidth approaches zero, one would expect the value to approach 1.414, the value for a sinusoidal excitation.

For each of the sets of data, the mean and standard deviation was calculated. The mean and two-sigma range, where one sigma is set equal to the standard deviation, are given in Figures A-7 and A-8. The two-sigma level was chosen because the majority of points calculated fall within this range. As was evident in Figure A-7, there is significant scatter. It is interesting to note that the two-sigma range for the larger bandwidths at each of the center frequencies is smaller than the range for the smaller bandwidths. This is primarily due to the fact that each of the corresponding time histories has a significant amount of low frequency energy. This low frequency energy controls the level and the scatter band decrease. There is some indication that a similar phenomenon occurs at the low bandwidths as well (i.e., 20 Hz center frequency with 1.5 Hz bandwidth). Again, this is due to the nature of the signal, such as a narrowband random approaching sinusoidal, that normally has less scatter.

Upon further study of the data given in Figure A-7, it was noted that a further correlation could be made for the mean values of the maximum amplification factors. By plotting these factors against bandwidth/center frequency ratio (BW/CF) it was found that all three curves in Figure A-7 collapse onto the single curve shown in Figure A-9. Thus, the values extend from a factor of 10.0 for a sine dwell, to about 1.8 for the broadest possible bandwidth at BW/CF = 2.0.

Note that this value is the maximum possible, since by definition no bandwidth can be wider than twice the center frequency. Furthermore, a transition region has been estimated, above which the signals are more deterministic (i.e., sine dwell and sine beat), and below which the signals are essentially Gaussian random. This transition region is estimated by

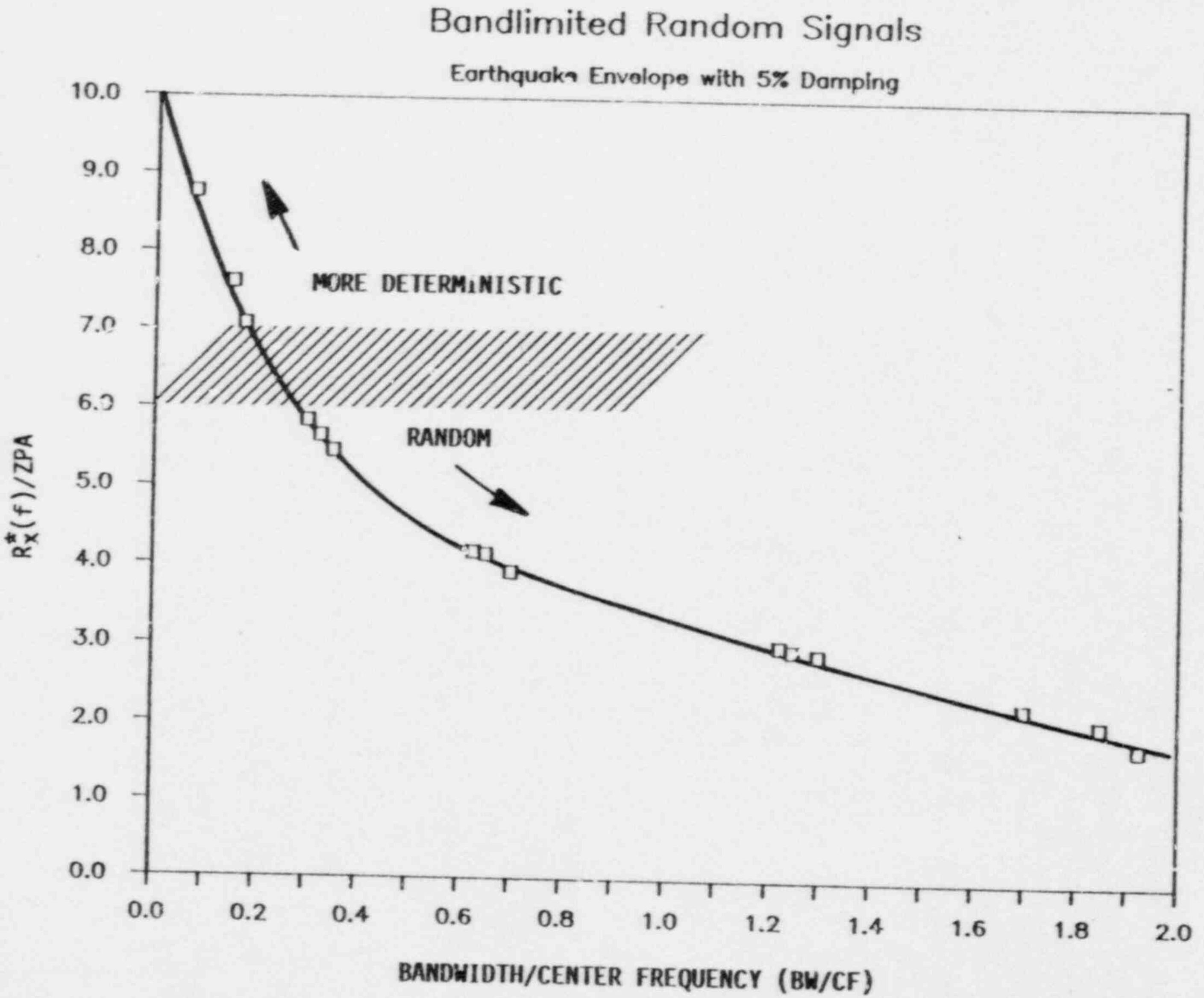


Figure A-9. Mean values for maximum amplification factor produced by various waveforms noting that Figure A-9 represents a cross plot of data from Figure A-1 at a damping value of β = 5%. This result alone can be useful in synthesizing signals to represent given response spectra.

By further comparing Figures A-1 and A-9, it is easy to estimate what happens for values of damping other than 5%. A family of curves would result, with those for lower values of damping falling above that for 5% in Figure A-9, and those for higher values of damping falling below the 5% curve. For a given value of damping, each curve represents a convenient means to show waveform similarity for given response spectra. This will now be demonstrated for the 5% curve given in Figure A-9.

In Figure 9 of the main report, $R_{x1}(f)$ and $R_{x2}(f)$ are two constituent spectra for which a composite is to be drawn. The maximum amplification factors, $R_x^*(f)/ZPA$, for these curves are given in the figure. The bandwidths and associated center frequencies for each spectrum can be obtained at 0.8 of the peak response values. Thus, for $R_{x1}(f)$, the bandwidth and center frequency are, respectively, about 8 Hz and 7 Hz with BW/CF = 1.14; while for $R_{x2}(f)$, they are about 7 Hz and 13.5 Hz with BW/CF = 0.52. By entering Figure A-9 with these parameters, along with the respective amplification factors, it can be seen that both sets of data fall near the curve, and the spectra represent random motion. Any composite spectrum developed from these spectra must also fit this region of the curve in Figure A-9. Therefore, if its peak spectral value is chosen to be about 2.0 g (so as to be enveloped by both $R_{x1}(f)$ and $R_{x2}(f)$ in the bandwidth 7.5 Hz to 12 Hz), what choices of bandwidth and center frequency are compatible with $R_{x1}(f)$ and $R_{x2}(f)$? By entering Figure A-9 at a $R_x^*(f)/ZPA$ ratio of 2.0, it can be seen that BW/CF = 1.7 to 1.9 is an appropriate value. Therefore, a composite having bandwidth from 2.0 to 23 Hz centered at 12 Hz is acceptable (i.e., BW/CF = 1.75).

Based on the analysis of data for simple, flat response spectra, the following conclusions can be made:

(1) The maximum amplification factor obtained from a given response spectrum can be used to indicate the nature of a time history that is compatible with the response spectrum. Generally, this can be done by determining its location on Figure A-9. Thus, two spectra can be shown to include waveform similarity by comparing their positions on Figure A-9, or simply by assuring that they have approximately equal maximum amplification factors.

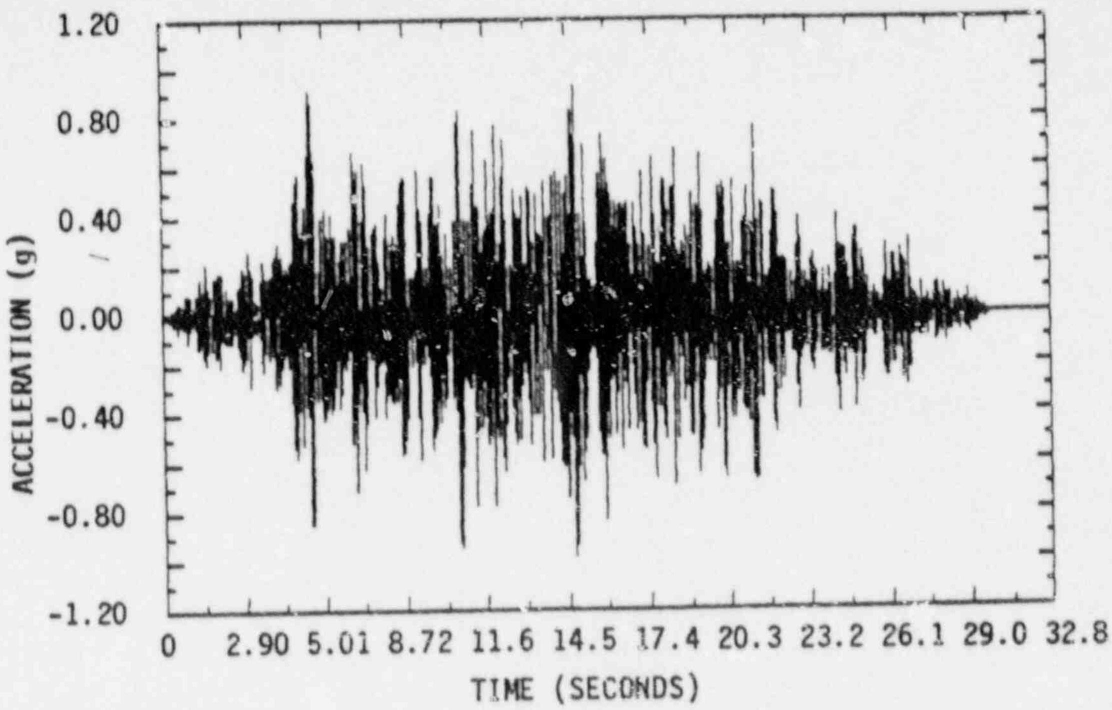
(2) Most spectra which have been specified in equipment qualification procedures appear to fit the broadband category defined in Figure A-9. Thus, random waveforms can most appropriately be used for their representation. For this, it should be noted that with a given value of damping, the maximum amplification factor is a function of both bandwidth and center frequency.

A3. COMPLEX RESPONSE SPECTRA

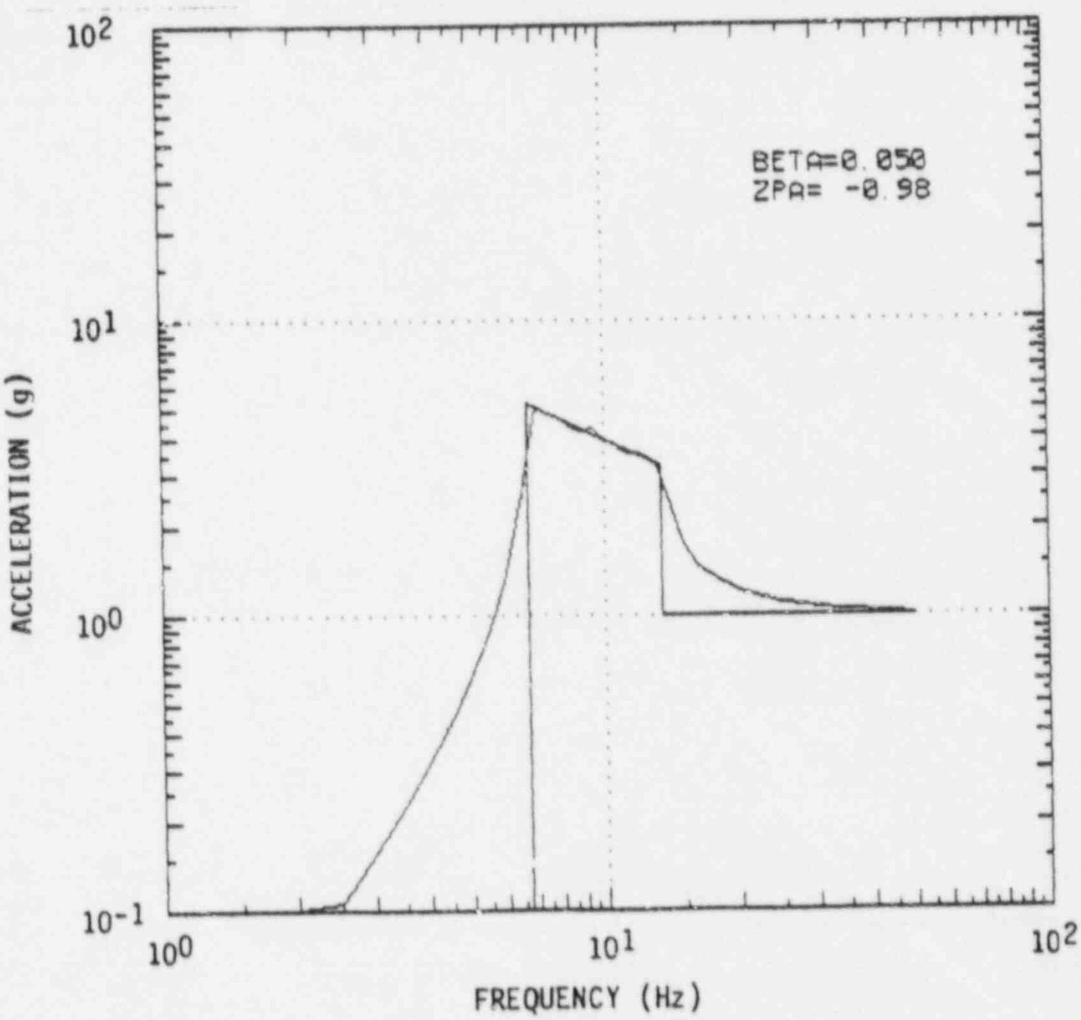
In many cases, the response spectra generated during qualification programs are not as simple as the single amplified region used in the analysis described above. It is therefore necessary to look at more complex spectra. One variation to be considered is a single peaked spectra whose amplified region is sloped. It is also appropriate to look at multipeaked spectra. For this case, the number of peaks, the relationship between the center frequencies of the peaks, the individual bandwidths and their relationship to each other, and the height of each peak and their relationship to each other are important factors. Limited analysis of these conditions will be made to determine how the simplified theory can be adapted to these more complex conditions.

A3.1 Sloped Response Spectra

Typical data for sloped response spectra are given in Figures A-10 and A-11. For the case studied, a center frequency of 10 Hz was chosen. In all cases, the amplitude of the response spectrum was chosen such that the low frequency spectral value was twice the high frequency spectral value. For example, at a bandwidth of 6.5 Hz, the spectral value at 6.75 Hz was 5.2, and the spectral value at 13.25 Hz was 3.2. The results indicate that



a) Time history



b) Shock spectrum

Figure A-10. Sloped response spectrum with 10 Hz center frequency and 6.5 Hz bandwidth

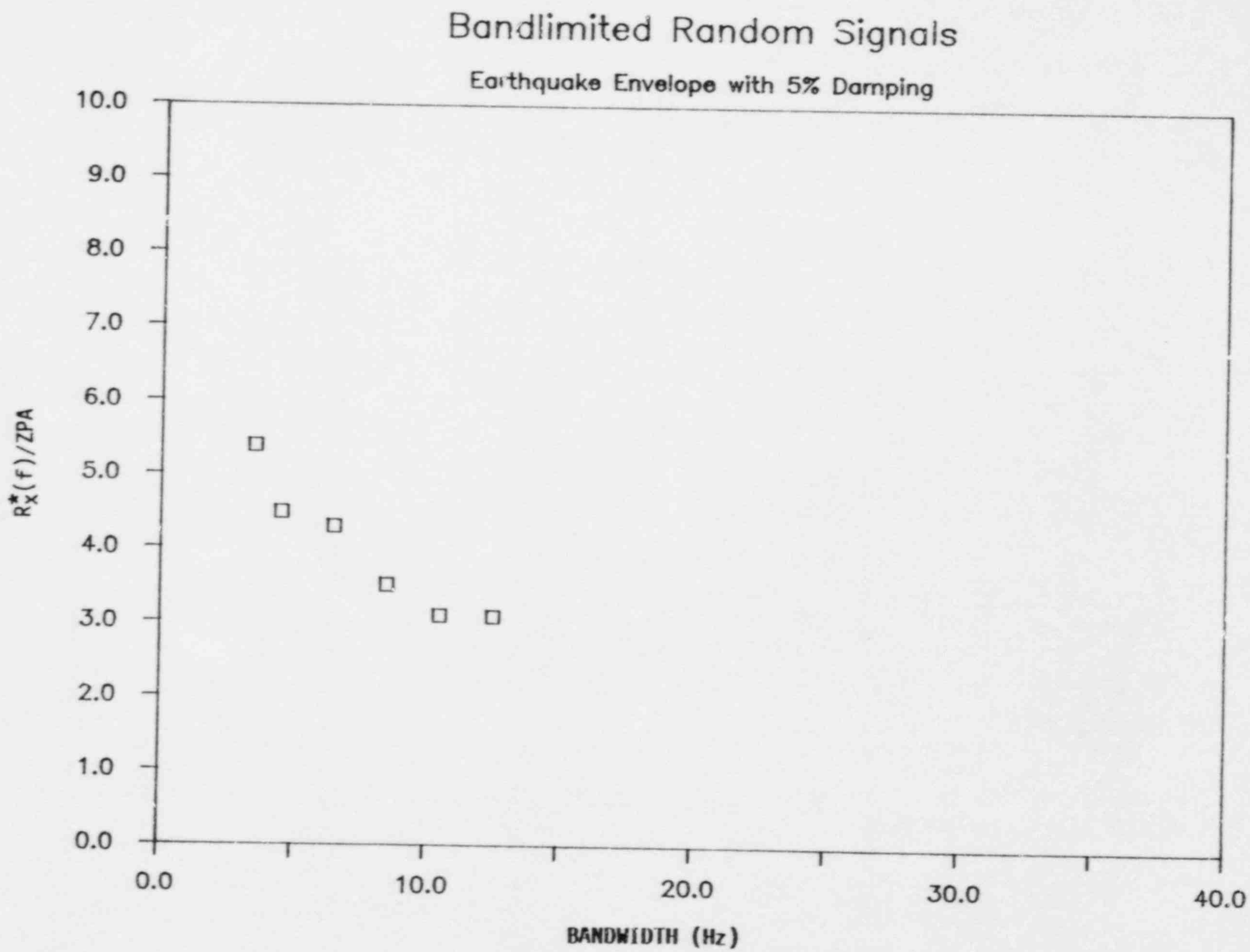


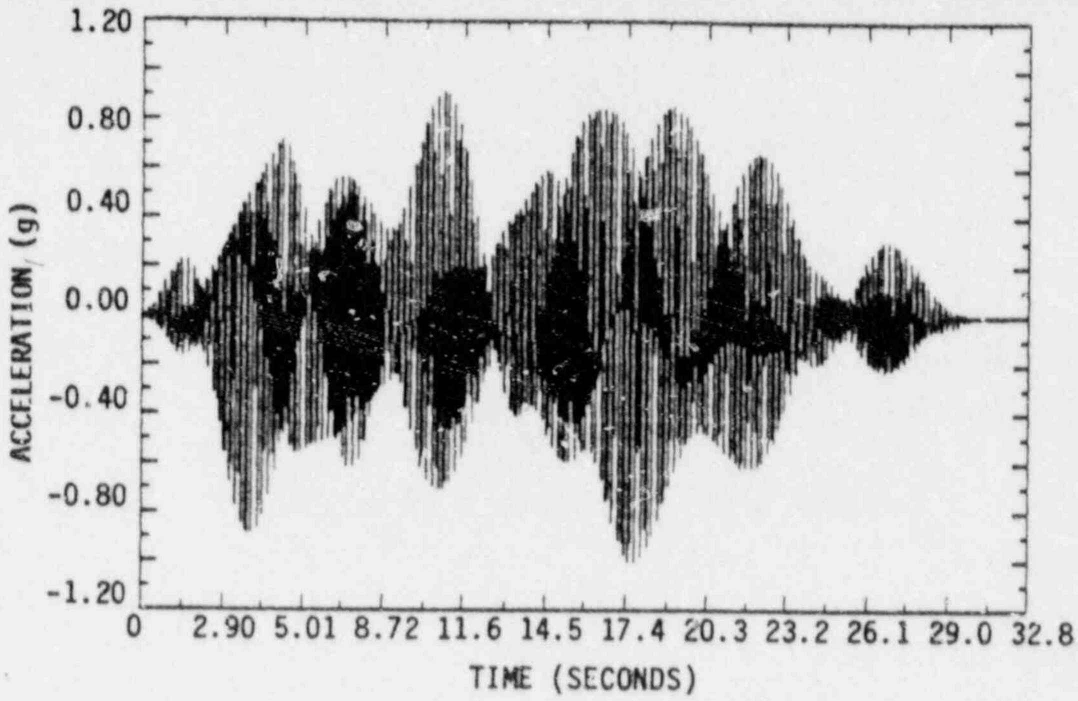
Figure A-11. Sloped response spectra data for 10 Hz center frequency use of the average spectral value in calculating the $R_x^*(f)/ZPA$ ratio produces data which lies on the curve for a flat response spectrum of the same center frequency. Therefore, to show similarity for sloped response spectra, the limited data indicate that it is only necessary to determine the average spectral value for a given center frequency and bandwidth. The bandwidth is determined again at 0.8 times the average peak spectral value.

A3.2 Multipeaked Response Spectra

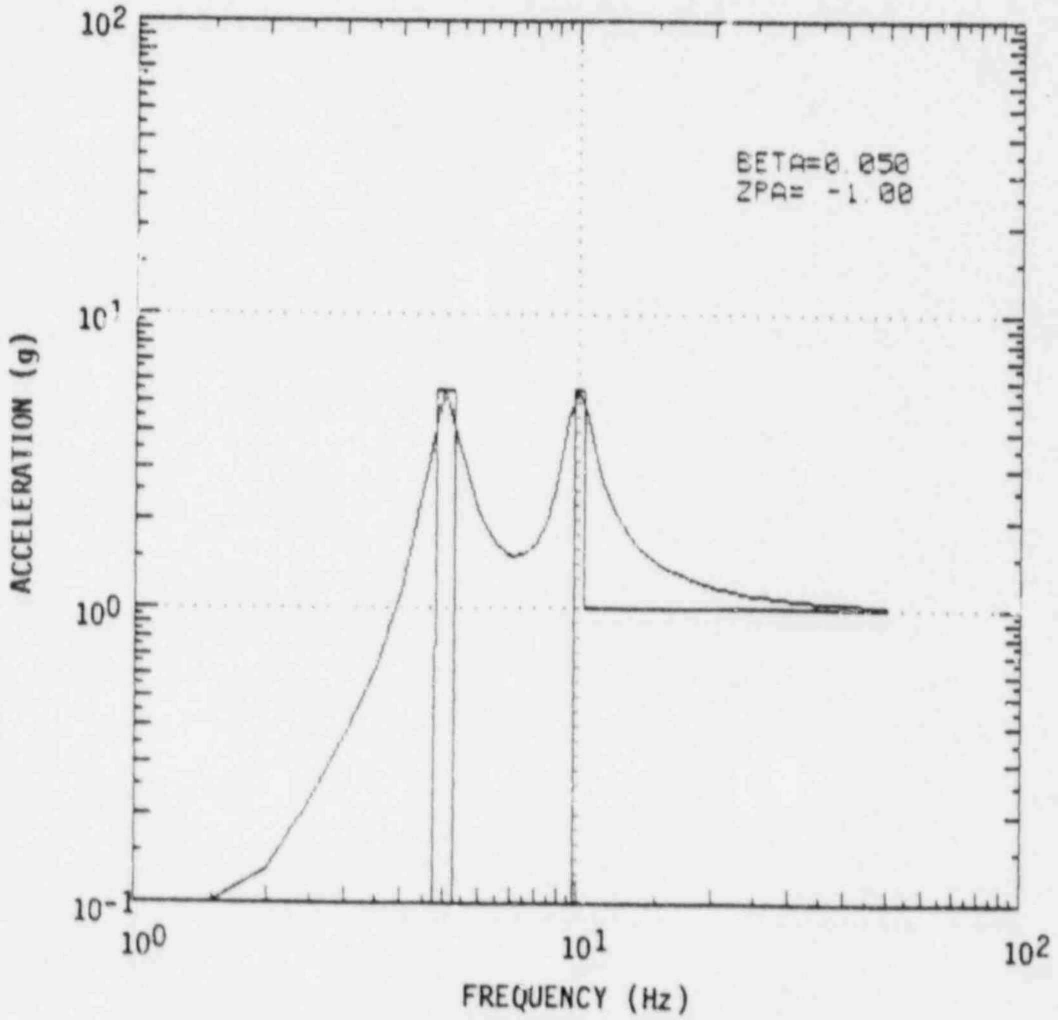
It is now appropriate to look at more complex response spectra and determine how the simplified theory defined above can be adapted to them. In the general case, multiple amplified regions can occur in qualification response spectra. The spectral level and bandwidth of these individual amplified regions can be any relation to each other. The first condition studied was one in which the spectral values of each of the amplified regions were equal. Example response spectra and corresponding time histories are given in Figures A-12 to A-15. Summary data for these cases are given in Figures A-16 and A-17.

The most obvious observation from the $R_x^*(f)/ZPA$ data is that the value for the zero bandwidth condition does not approach the $1/2\beta$ level previously given in Figure A-7. When one looks at the time histories for these conditions, Figure A-12 for example, the reason is obvious. Because of the presence of two widely separated frequencies, the signal never approaches the sinusoidal excitation condition. In fact, the level of the signal with three distinct amplified regions does not reach that of the signal with two amplified regions. The data tends to indicate that the level of the zero bandwidth approaches a value given by:

$$R_x^*(f)/ZPA(bw - 0) = (1/2\beta)/N \qquad \text{(A-6)}$$

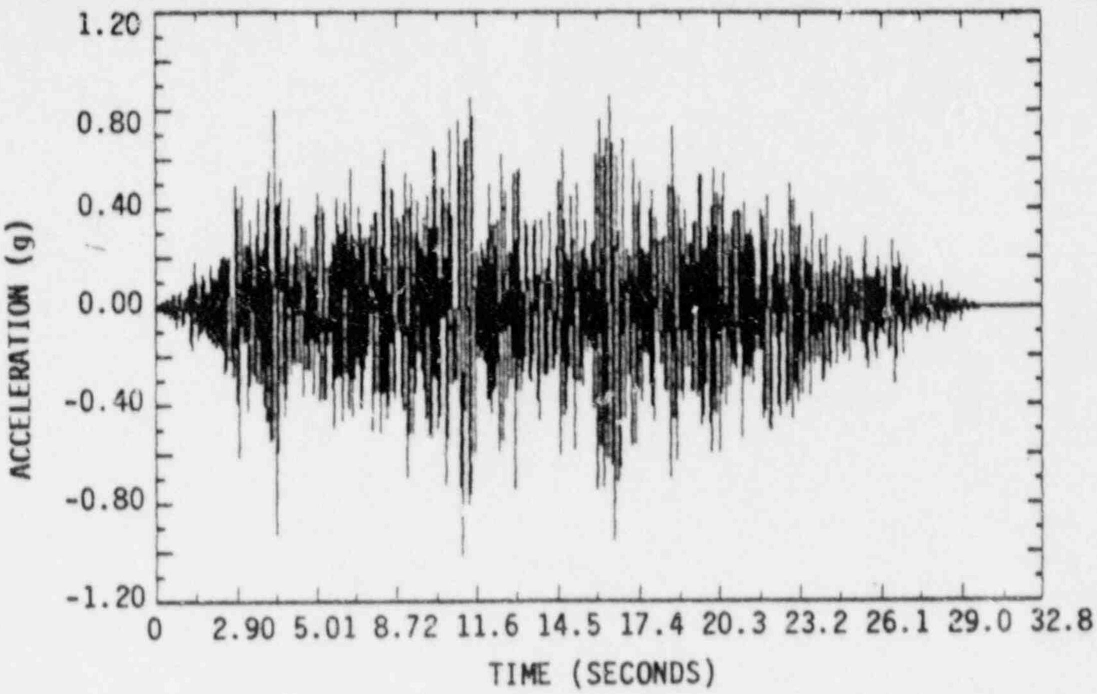


a) Time history

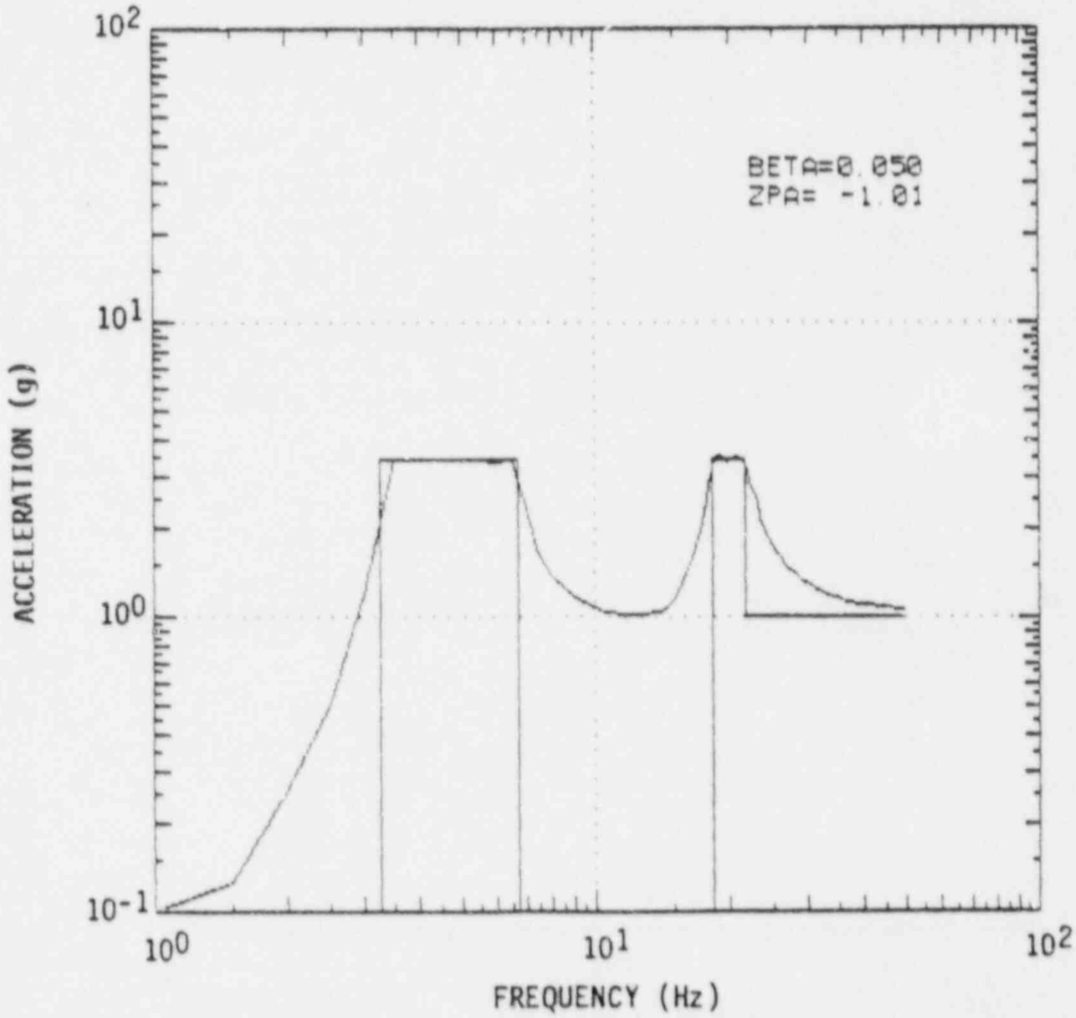


b) Response spectrum

Figure A-12. 5 and 10 Hz center frequencies, each with 0.5 Hz bandwidths

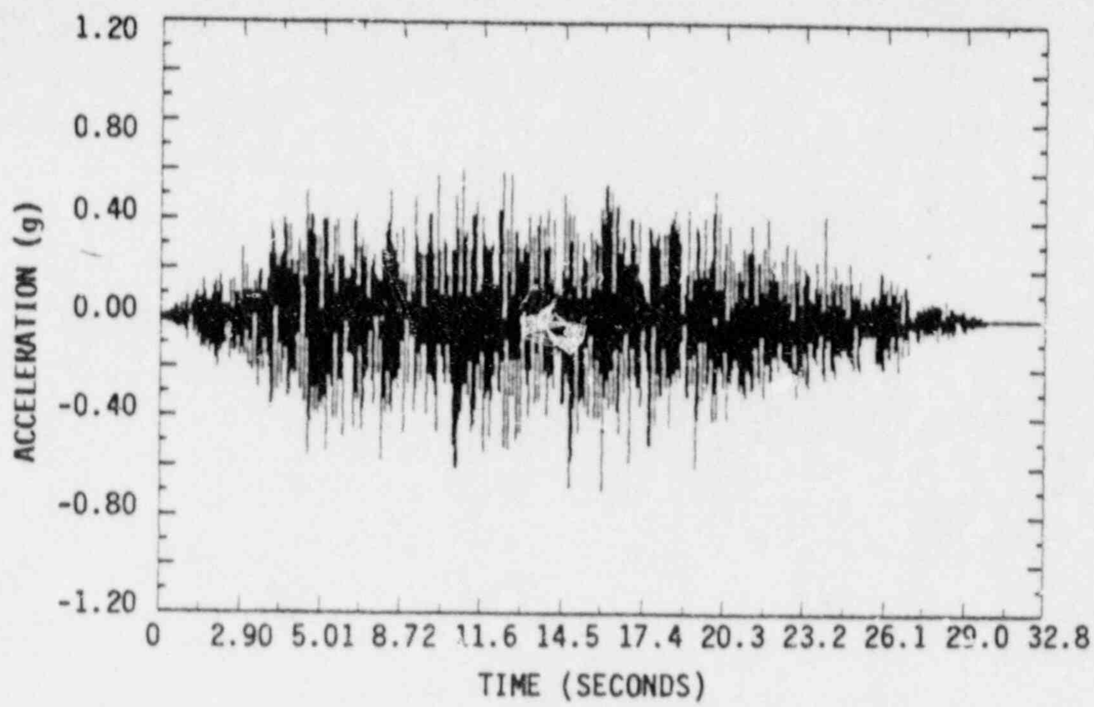


a) Time history

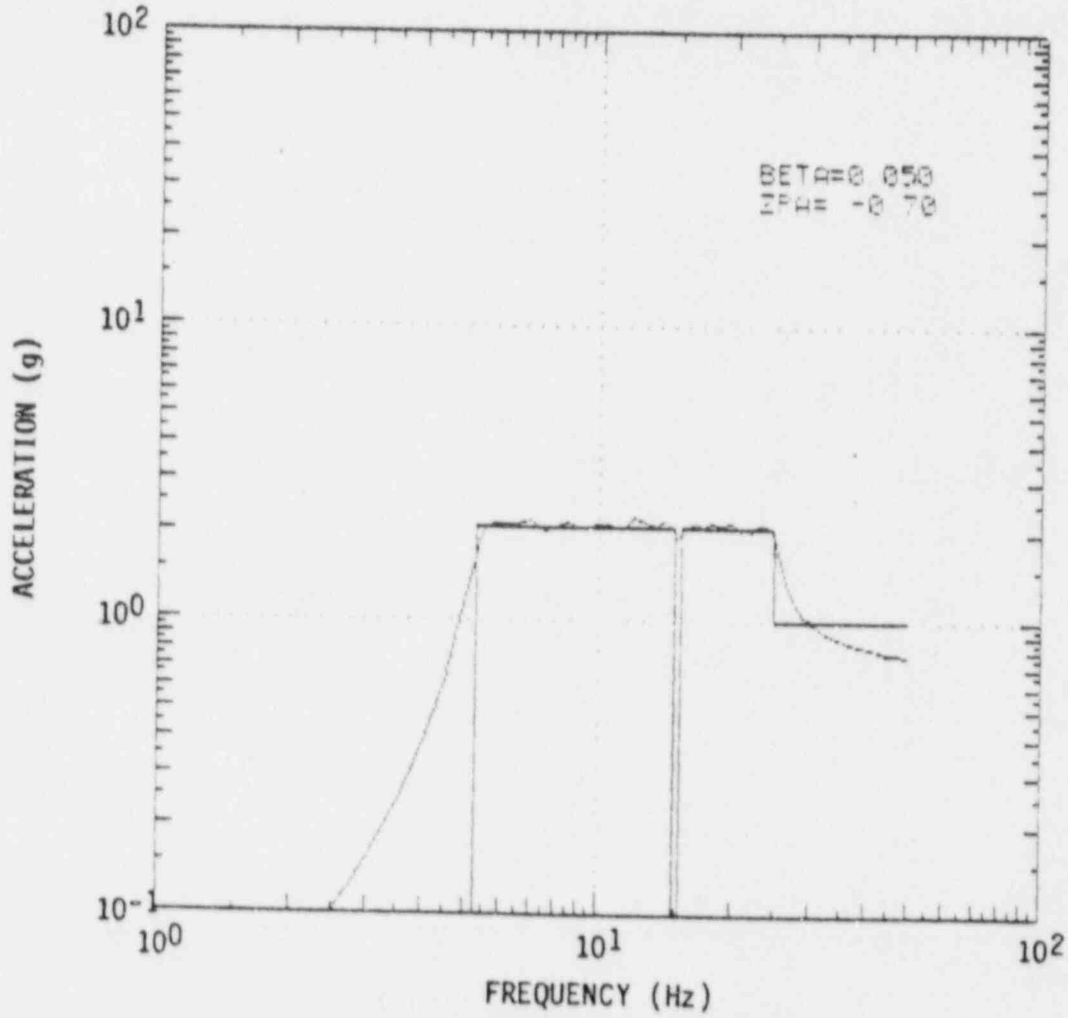


b) Response spectrum

Figure A-13. 5 and 20 Hz center frequencies, each with 3.5 Hz bandwidths

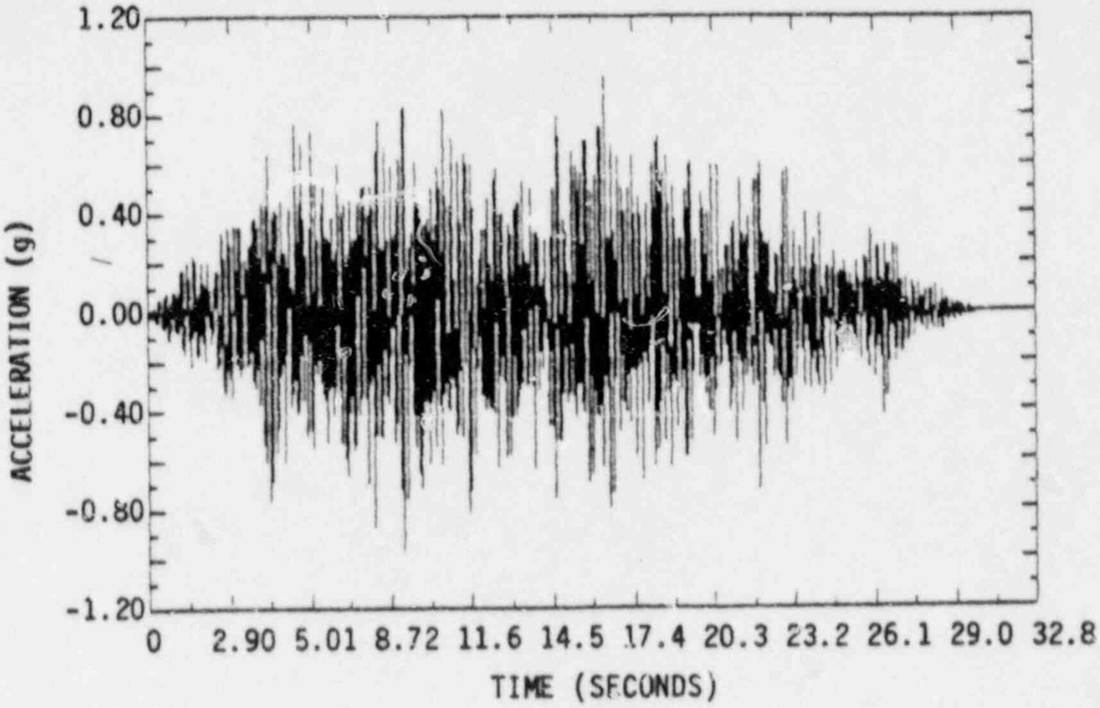


a) Time history

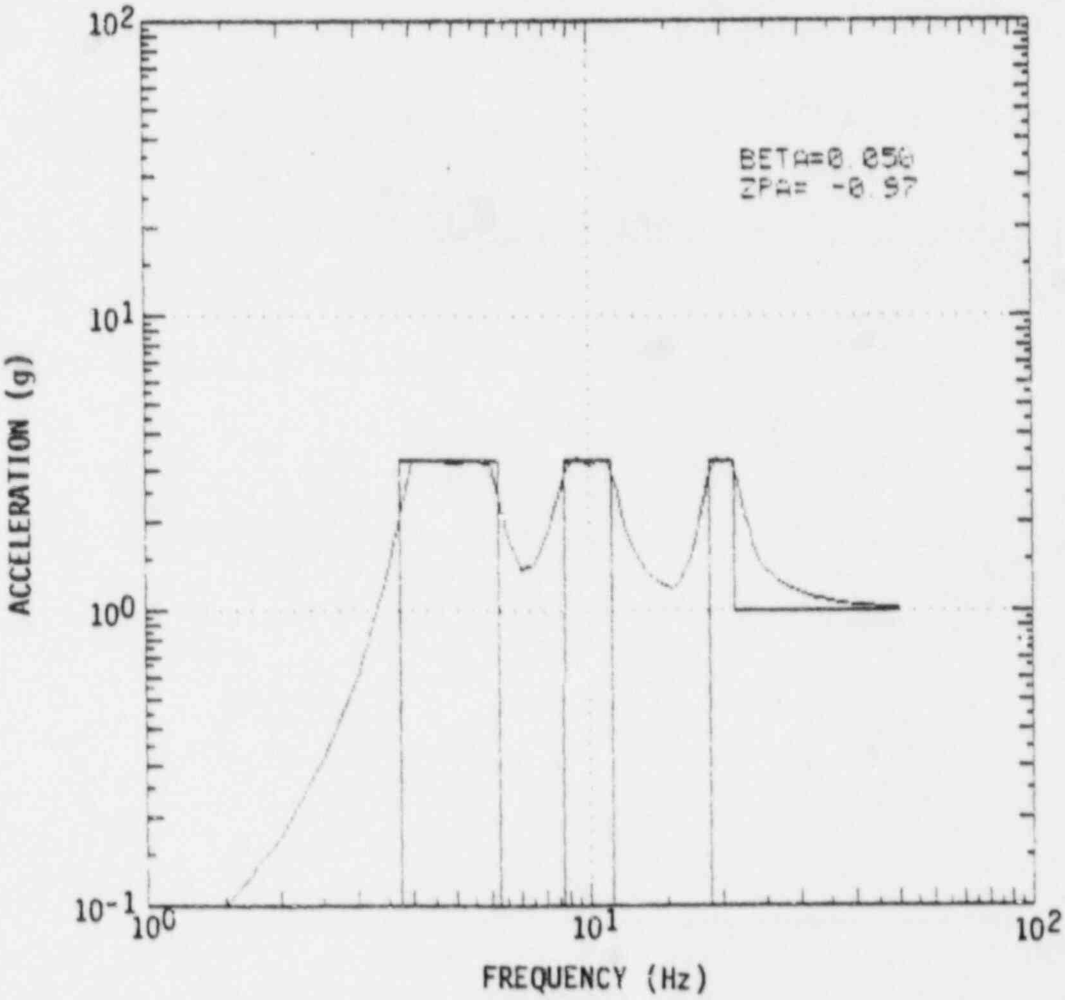


b) Response spectrum

Figure A-14. 10 and 20 Hz center frequencies, each with 9.5 Hz bandwidths



a) Time history



b) Response spectrum

Figure A-15. 5, 10 and 20 Hz center frequencies, each with 2.5 Hz bandwidths

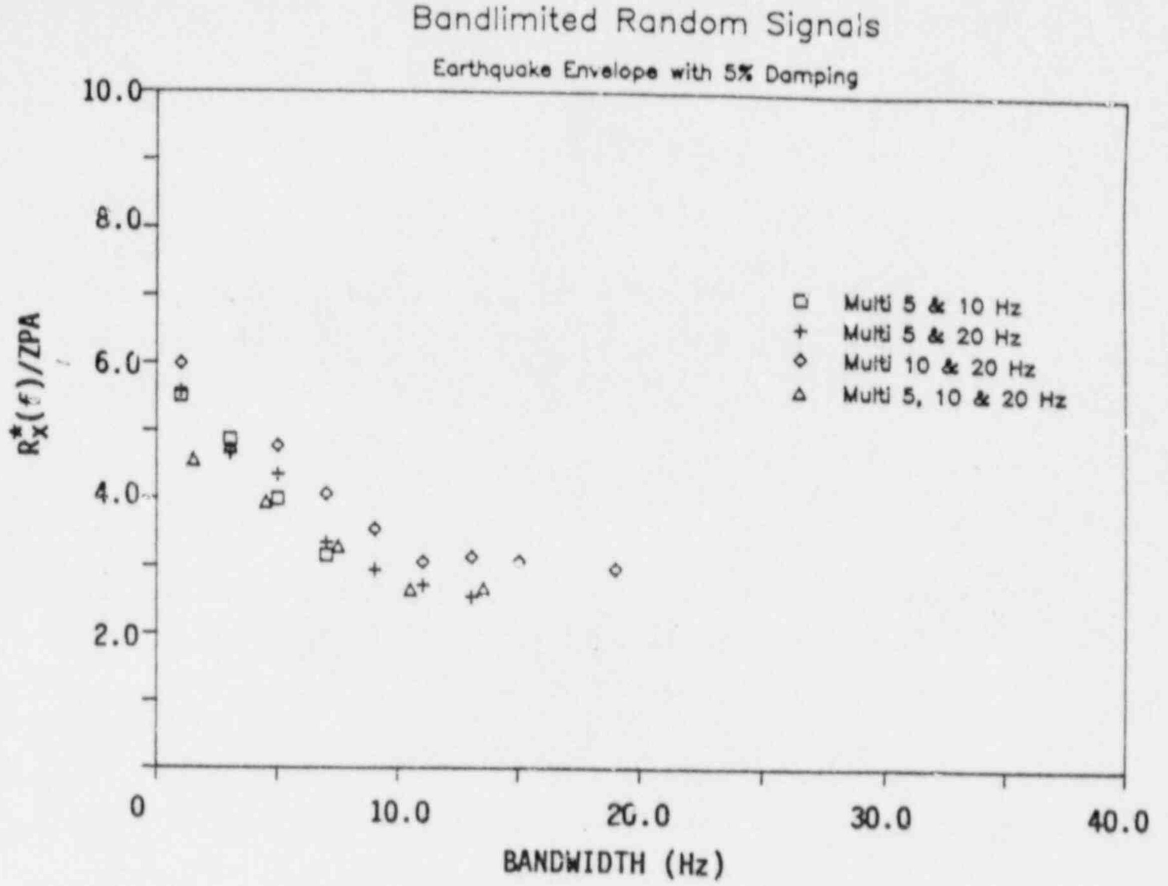


Figure A-16. $R_x^*(f)$/ZPA ratio as a function of bandwidth for multipeaked signals

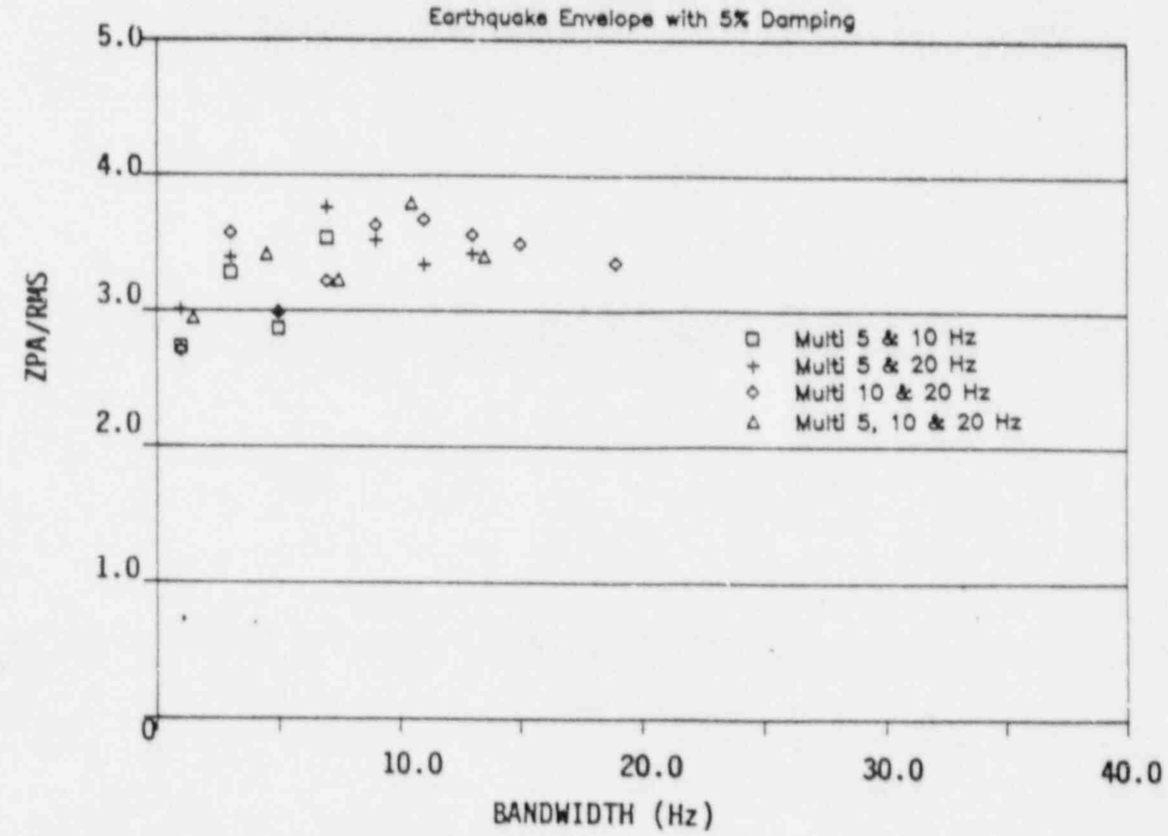


Figure A-17. ZPA/RMS ratio as a function of bandwidth for multipeaked signals where N is the number of amplified regions. As the number of amplified regions becomes large, i.e., greater than 10, the validity of this formulation is unknown.

A second observation is that the data follows a similar trend to that given in Figure A-7, in that the shape of the curves are similar. Since the spectral levels of the amplified regions in this analysis are equal, the $R_x^*(f)$/ZPA data plotted in Figure A-16 is based on that level. Because of this and the fact that the individual bandwidths are constant, the contributions of each of the amplified regions are not taken independently in this plot. The bandwidth indicated is the sum of the bandwidths of the various amplified regions.

For the pairs with center frequencies of 5 and 10 Hz and 10 and 20 Hz, the large bandwidth limit seems to be approaching a value that is related to that for a single amplified region with a center frequency at the average of the two amplified regions. For the 5 and 20 Hz pair, it is not possible to make this same statement since the individual frequency bands do not come close enough together because of the one hertz low frequency limit on the 5 Hz component.

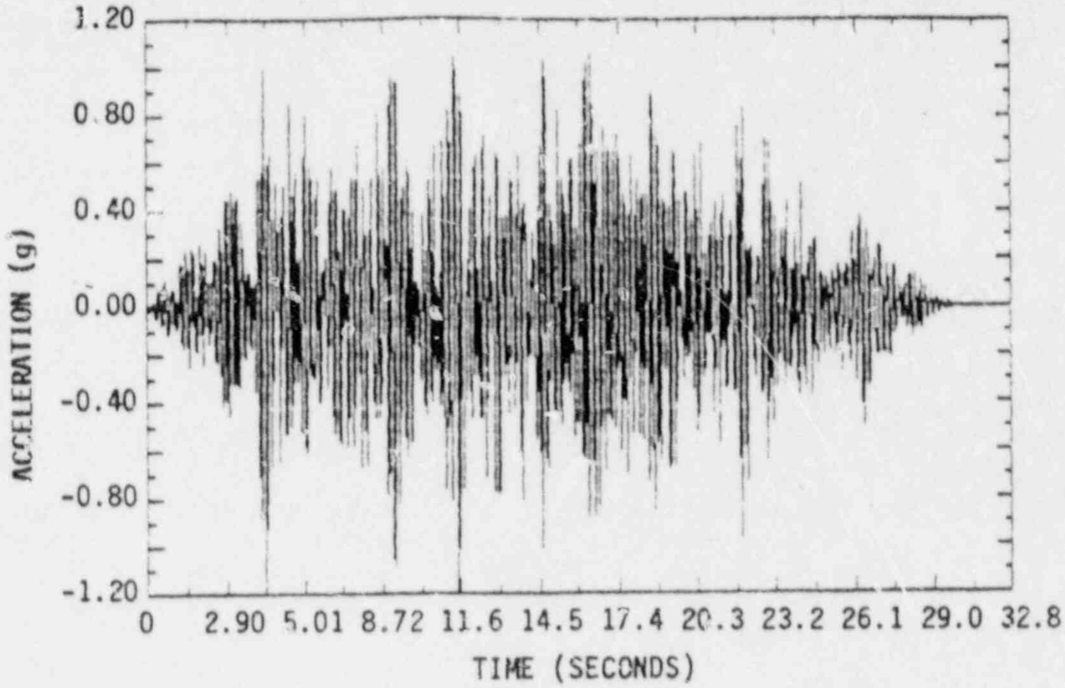
Methods of deriving the maximum amplification factor for a complex spectrum were based on some average combination of individual simple spectra. The desired result was to produce an amplification factor which was equal to that obtained from the corresponding time history for a given complex spectrum. However, it became apparent that a sum of the individual amplified regions divided by the number of regions was not an acceptable approach. This average resulted in predicted values for two amplified regions as much as 70% high and the case for three amplified regions more than double. A more acceptable approach was a squareroot of the sum of the squares combination, divided by the number of regions. If the components calculated from the various amplified regions are combined in this manner, the predicted $R_x^*(f)$/ZPA ratio is within 30% of the time history results

In all cases, the spectrally-derived value is higher. Therefore, if one is considering a composite spectrum from broadband random signals, the theoretical results will be on the conservative side, i.e., indicate a more narrowband signal than is actually present. For the majority of the cases, the accuracy of the results are controlled by the effects of the high frequency component. This is particularly true for any case with a 20 Hz center frequency signal. The above method results in accuracy that is comparable to data for a simple response spectrum.

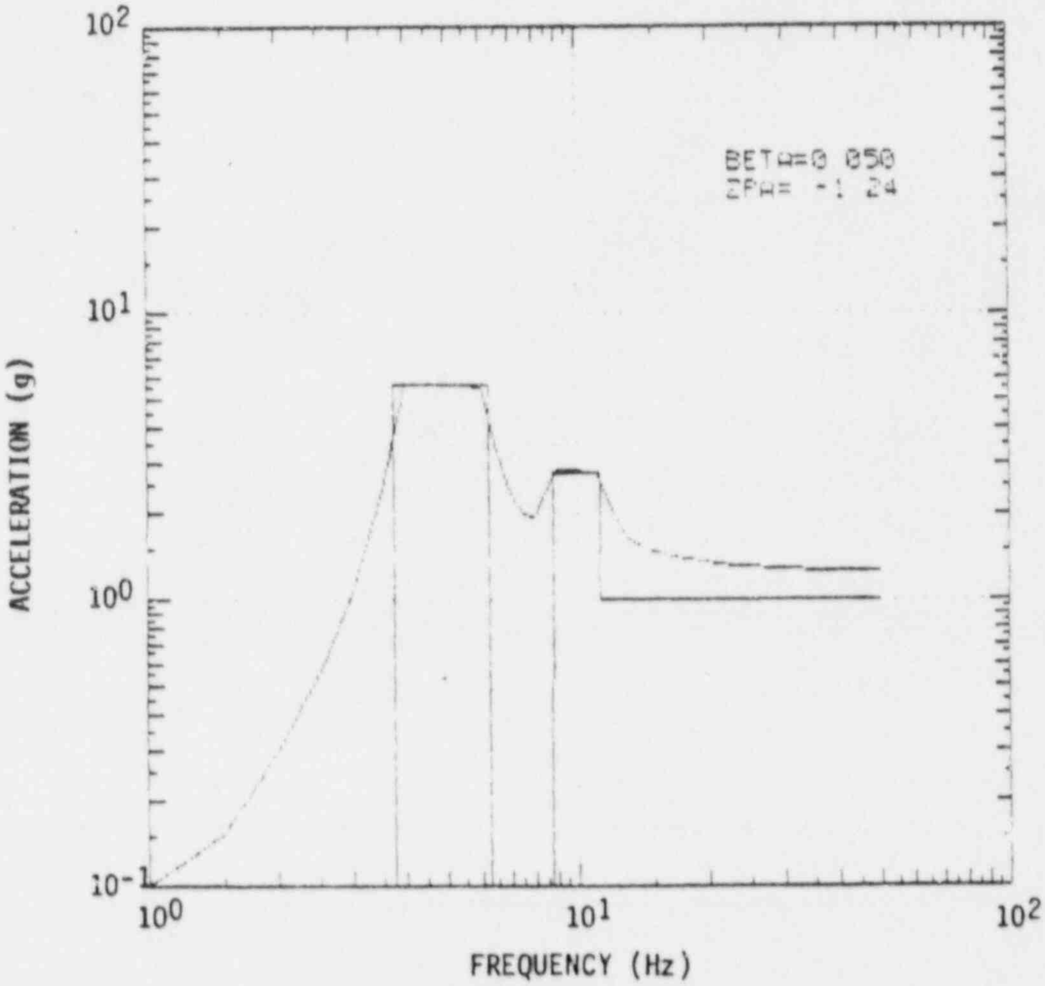
The next step is to consider the case where the spectral values of the individual regions are not equal. For this, the ratio of the two peak spectral levels was set at a value of 2.0. Sample response spectra and corresponding time histories are given in Figures A-18 and A-19. The $R_x^*(f)/ZPA$ ratios for these cases are given in Figures A-20 (5 and 10 Hz), A-21 (5 and 20 Hz) and A-22 (10 and 20 Hz). Three different values of the ratio are plotted for each point. They are based on the high, low, and average spectral values. If one compares the average results to those of the condition with equal height amplified regions, discussed above, the results match well. For the case analyzed, with equal bandwidths in each region, the determination of similarity of waveforms should be based on the average spectral level.

A4. RESULTS AND CONCLUSIONS

The maximum amplification factor derived from response spectra has been shown to be an acceptable parameter to demonstrate similarity of waveforms. Similarity is required in the development of a composite spectrum from experience data to insure that the various component spectra utilized to derive the composite will produce similar failures in the item. The applicability of this ratio has been derived from the analysis of a number of time histories shaped to a variety of response spectra. The response spectra utilized varied from very simple ones with one flat amplified region to more complex ones with multiple amplified regions. Maximum amplification factors for complex spectra were derived by combinations of simple spectra.

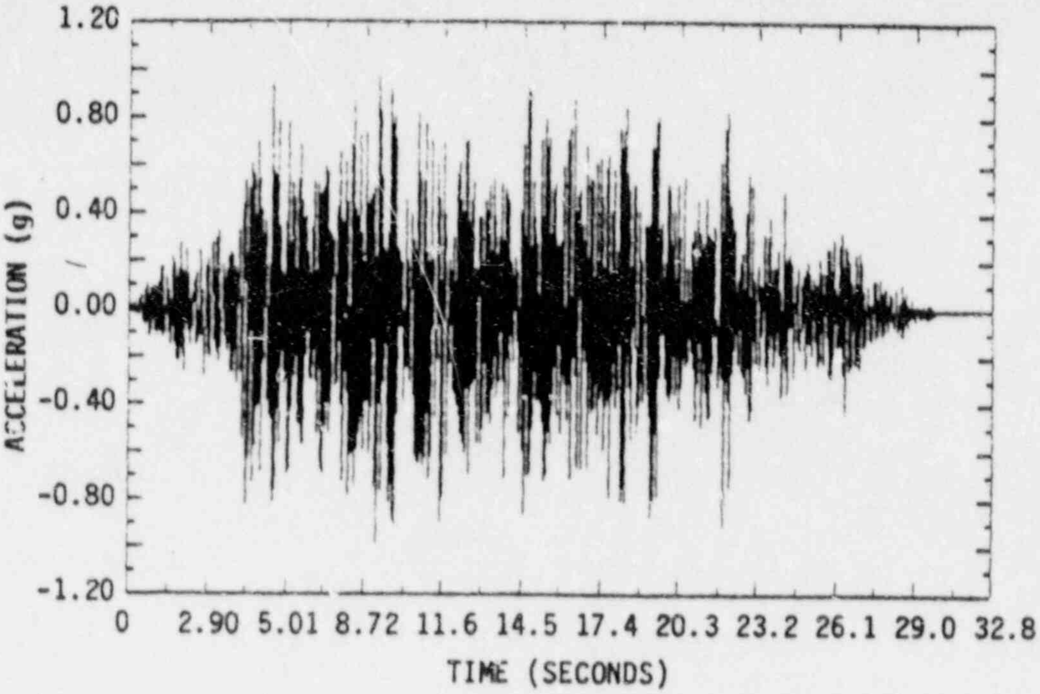


a) Time history

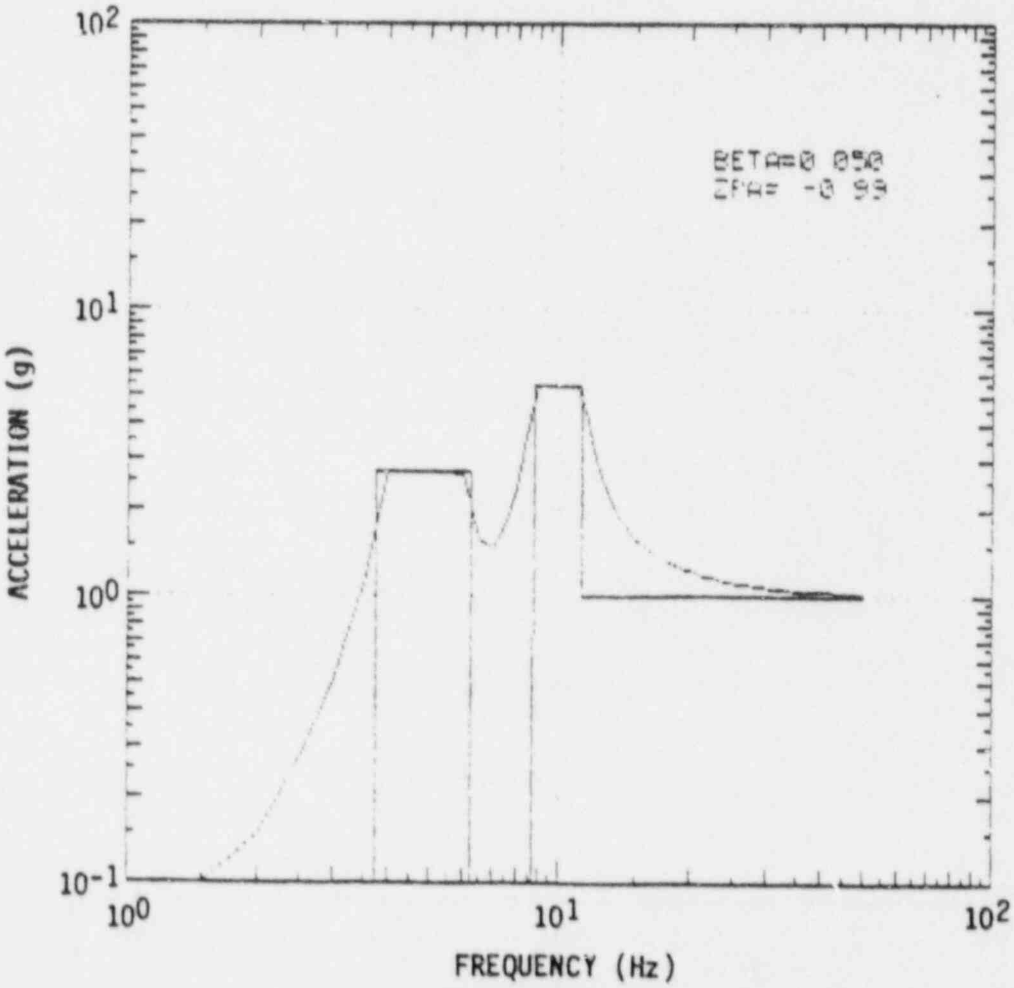


b) Response spectrum

Figure A-18. Variable height low frequency high, multipeaked spectrum 5 and 10 Hz center frequencies, each with 2.5 Hz bandwidths



a) Time history



b) Shock spectrum

Figure A-19. Variable height high frequency high, multipeaked spectrum 5 and 10 Hz center frequencies, each with 2.5 Hz bandwidths

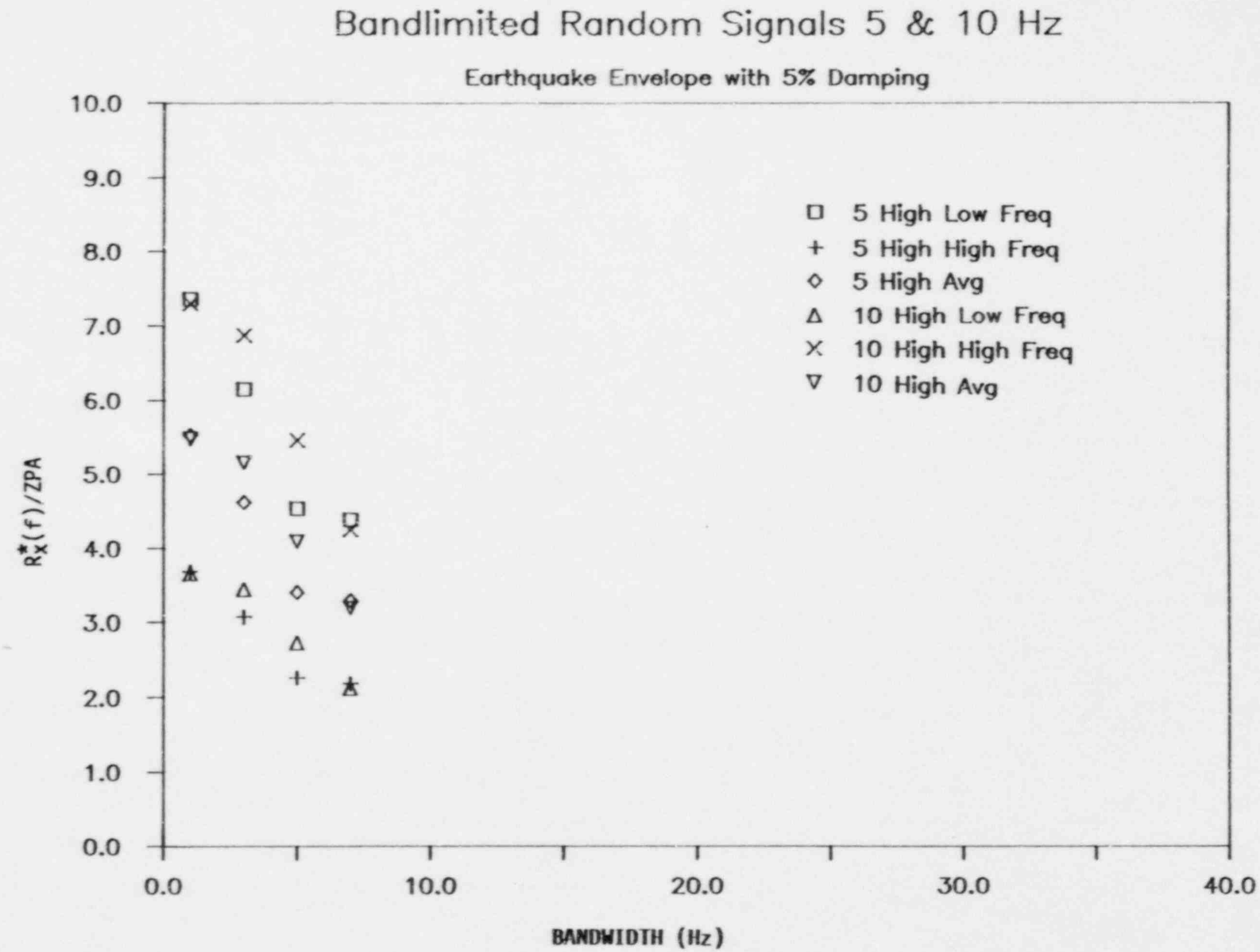


Figure A-20. $R_X^*(f)$/ZPA ratio for variable height multipeaked spectra 5 and 10 Hz center frequencies

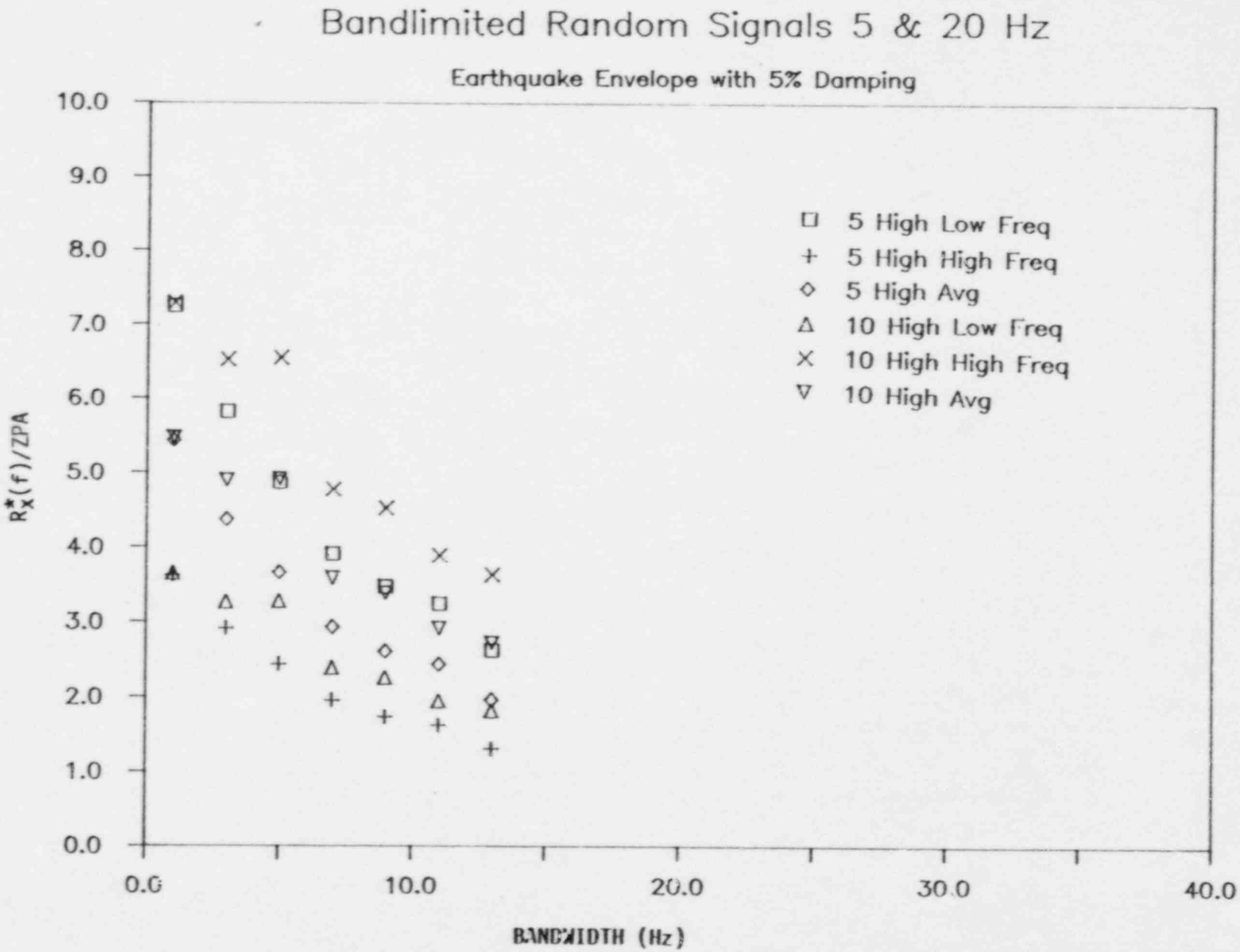


Figure A-21. $R_x^*(f)/ZPA$ ratio for variable height multipeaked spectra 5 and 20 Hz center frequencies

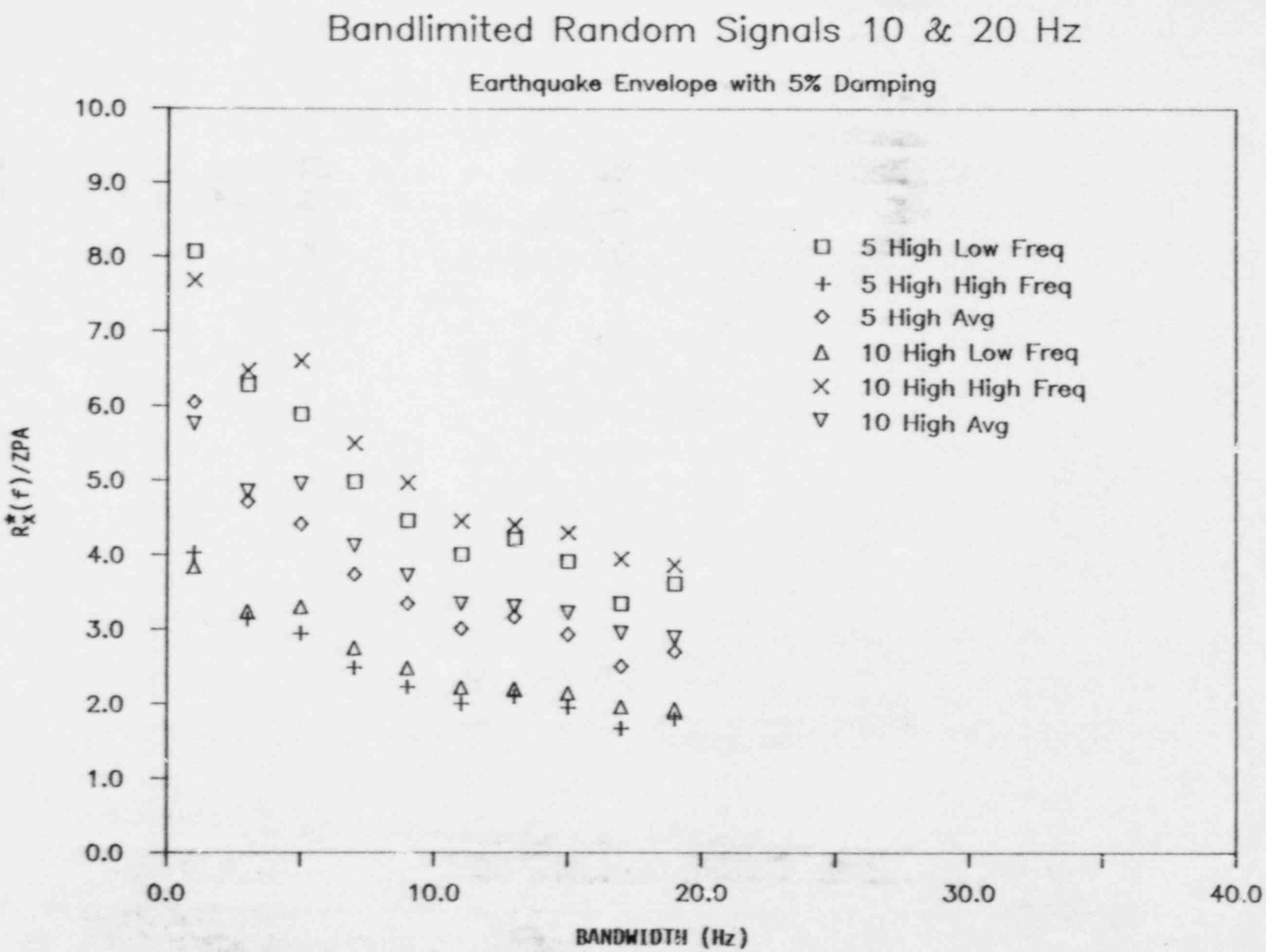


Figure A-22. $R_x^*(f)$/ZPA ratio for variable height multipeaked spectra 10 and 20 Hz center frequencies

Although all analyses were performed for 5% damping, it would appear that similar relative results would be obtained at other values of damping. This is based on the data presented in Figures A-1 and A-9.

Since the approach to establishing maximum amplification factors for complex spectra is based on average combinations of individual spectra, the two conclusions given at the end of Section A2.1 are also applicable to complex spectra.

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13. ABSTRACT (200 words or less)

A methodology is developed for seismic qualification of nuclear plant equipment by applying similarity principles to existing experience data. Experience data are available from previous qualifications by analysis or testing, or from actual earthquake events. Similarity principles are defined in terms of excitation, equipment physical characteristics, and equipment response. Physical similarity is further defined in terms of a critical transfer function for response at a location on a primary structure, whose response can be assumed directly related to ultimate fragility of the item under elevated levels of excitation. Procedures are developed for combining experience data into composite specifications for qualification of equipment that can be shown to be physically similar to the reference equipment. Other procedures are developed for extending qualifications beyond the original specifications under certain conditions. Some examples for application of the procedures and verification of them are given for certain cases that can be approximated by a two degree of freedom simple primary/secondary system. Other examples are based on use of actual test data available from previous qualifications. Relationships of the developments with other previously-published methods are discussed. The developments are intended to elaborate on the rather broad revised guidelines developed by the IEEE 344 Standards Committee for equipment qualification in new nuclear plants. However, the results also contribute to filling a gap that exists between the IEEE 344 methodology and that previously developed by the Seismic Qualification Utilities Group. The relationship of the results to safety margin technology is also discussed.

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