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

Task 3: Recommendations for Improvement of Equipment Qualification Methodology and Criteria

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Prepared for
U.S. Nuclear Regulatory
Commission

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Task 3: Recommendations for Improvement of Equipment Qualification Methodology and Criteria

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PREFACE

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

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

Specifically, this document constitutes the Task 3 Summary Report. Other reports previously published under Task 1 are listed as References 1, 2, and 3 on the list given at the end of this report. Work on Task 4 is in progress, and will be reported in the last-indicated summary report.

1.0 INTRODUCTION

Qualification of nuclear plant equipment has developed from its infancy to a complex methodology over the last fifteen years. Most of this development has been directed toward seismic qualification which has been governed first by IEEE Standard 344-1971, and later by IEEE Standard 344-1975. Qualification to seismic and other environments has been governed by IEEE Standard 323-1974. In addition, a whole series of other industrial standards and U.S. NRC Regulatory Guides form a library of governing documents that have evolved along with the developing methodology.

In order to assess the consistency and adequacy of the qualification methodology and the standards for implementing it, the NRC has sponsored several research programs aimed at reviewing the state of the art, evaluating the current methodology, and making recommendations for improvements in the process. This report presents recommendations that have been developed under one of these programs.

The results presented herein are based on a research program that was initiated in June 1981, and has been directed primarily at seismic qualification of equipment. The program has occurred during the latter part of several years of deliberation that have been aimed at updating of IEEE Standard 344-1975. A close communication and participation has been maintained with the IEEE 344 revision committee efforts. Furthermore, the results of our program have been reviewed periodically by a Peer Review Group consisting of eleven well-known individuals selected from a cross-section of organizations that are engaged in various phases of the equipment qualification process. As a result, we feel that a particularly useful iteration of data development and information dissemination has been achieved. Thus, the recommendations given in this report are based on interaction with the IEEE 344 Revision Committee, personal communications with various engineers engaged in equipment qualification, and actual experience with equipment qualification ourselves, in addition to the results that we have developed on this research program to date.

For simplicity and directness, the format of this report will be to present a brief discussion followed by recommendations associated with each of a series of technical issues that have been found appropriate for consideration. More details of the identification and evaluation of these issues can be obtained from the three previous summary reports [1,2,3] published under this program, numerous references cited in those reports, as well as three technical papers [4,5,6] that have already been published to describe the findings. Some technical issues discussed are similar, and others different from those identified in a recent parallel review effort [7]. Herein we will describe each issue only sufficiently for its identification, so that recommendations for its disposition can be emphasized. The issues and recommendations have been grouped into five different categories, depending on how they may be implemented. The first four categories include issues for which enough information has been obtained to allow immediate recommendations. The priorities of individual issues in these categories are judged to be more or less equal. The final category involves unresolved issues, and of course must lead to recommendations for extended investigation. This last category includes the issue of fragility, which is receiving initial study under Task 4 of the current program, but is of such a magnitude that it will nevertheless require extended effort.

2.0 STANDARDIZATION OF PROCEDURES/INFORMATION

The historical development of the equipment qualification program has lead to a large variety of acceptable procedures and documents covering its applicability. Due to the complexity of equipment involved and the evolving requirements, it is often difficult to determine the relevant documents and/or procedures that apply for a specific hardware item. Since these procedures already have been accepted it is appropriate to standardize their application so that both the qualification and review programs can be expedited. We first consider several issues which fall under such standardization of efforts.

2.1 Equipment List and Standards

It has been only relatively recently that a more uniform agreement has been recognized as to just what actual hardware falls under the category of equipment which must be seismically qualified. Even so, whether a given device is considered electrical or mechanical is still often debated, and therefore questions arise as to which regulatory standards are applicable. Items which are assembled to form an operating nuclear power plant come in all shapes and sizes. Electronic and electrical items range, in size, from pieces of wire to assemblies of relays, instruments, etc., and mechanical items range in size, from small machine screws to vessels weighing more than 100 tons. This diverse array of equipment recently [1] has been classified into 11 generic groups defined to include all the mechanical and electrical components which must be qualified in any given nuclear plant. We have now reduced the list to 9 generic groups, as shown in Table 2.1, which are further divided into subgroups according to size and function. The items deleted from the original list in Reference [1] were subsequently considered to be passive structural components, rather than electrical or mechanical equipment. Thus, the items remaining in Table 2.1 are of primary concern in this program.

Categorization of equipment as either mechanical or electrical can be determined by consideration of either the physical characteristics of the device, or system, or its function. Physical characteristics are appropriate when considering a single device but become clouded for

TABLE 2.1 EQUIPMENT AND COMPONENT CATEGORIZATION

Generic Group	Generic Subgroup	Primary Function*
Electric Equipment Mounts	Panels	M
	Racks	M
	Cabinets	M
Electrical Instrument and Devices	Transducers Including Integral Signal Conditioners	E
	Computer Systems	E
	Communication Systems	E
Electrical Power Devices	Switch Gear	E
	Transformers	E
	Invertors	E
	Emergency Diesel Generators	E, M
	DC Power Limiters, e.g., Batteries, etc.	E
	Control Cabinets	E
Valves	Large Power Operated Valves Air or Electric	M
	Relief Valves	M
	Check Valves	M
	Instrumentation Valves	M
Pumps and Drives	Main Coolant Pumps	M
	Medium to Large Pumps and Compressors	M
	Safety Related Pumps	M

TABLE 2.1 EQUIPMENT AND COMPONENT CATEGORIZATION (continued)

Generic Group	Generic Subgroup	Primary Function*
Heat Removal Systems	Heat Exchangers	M
	Emergency Pump Drive Systems	M
	Large Cooling Fans, Motors and Generators	E, M
Air Conditioning Systems	Air Ducting Devices	M
	Air Conditioning and Filtering Devices	M
System Support Facilities	Cable Trays	M
	Fuel Storage Racks	M
Miscellaneous Components	Snubbers	M
	Fuel Rod Assemblies	M
	Control Rod Drive Mechanisms	M
	Reactor Internal Devices	M

---

* E - Electrical and Electronic
M - Mechanical

systems; for example a governor (mechanical) and control panel (electrical) for a generator set (electrical, mechanical). Consideration of the primary function of the device or system, which will most likely include the most probable failure mechanisms, can also be used to categorize the equipment.

In conjunction with the categorization of equipment it is also appropriate to develop a list of standards and requirements appropriate to each group. Reference [1] lists a number of NRC regulatory guides and industrial standards concerned with the qualification procedure. When and how to apply these documents is often difficult to determine. This is especially evident in the area of seismic qualification of mechanical equipment where no document, similar to IEEE-344, exists. The intent is to define procedures whereby the qualification and review process can be expedited.

Recommendations

1. A standard equipment list, similar to Table 2.1, should be adopted. Each piece of equipment requiring qualification should be placed in one of these categories. Justification of the selected category should be included in the qualification documents.
2. The categorization of equipment should be based on the primary function of the device or system.
3. After an equipment list has been standardized the existing regulatory guides and industrial standards applicable to each group should be defined and published as a separate document. This document list should be updated periodically as additional literature becomes available.
4. This action should be performed by the NRC with consultation from members of the industry.

2.2 Acceptance Criteria

Each piece of equipment requiring qualification must function before, during, and after the postulated seismic event. Procedures for measuring the functionality have been established and used in qualification programs. In the majority of qualification programs failures do not occur. However, difficulty arises in the definition of the functional parameters which consitute a "failure" in the event one does occur. In most cases qualification testing is performed on devices or systems which are parts of a much larger system. As a result, it is often difficult to determine at what level a malfunction becomes a failure. For example a relay may chatter, but if the duration of the chatter does not exceed a certain time, a solenoid downstream will not trip. The procedures for developing these acceptance criteria are available and in wide use.

In most qualification tests the most difficult task is the measurement of the functional parameters. The test procedures seldom contain justification of the acceptance criteria levels and therefore interpretation of the requirements and corresponding modification to the measurement procedures cannot be made. For example a pressure switch, with 10% tolerance on set points, is to be subjected to fluctuating pressure during the seismic event. The acceptance criteria is that the switch shall not chatter for greater than 2 msec. If a change of state occurs in the switch of 4 msec during the test a "failure" would be indicated, but after closer examination it may be found that this occurred while the pressure was within 10% of the set point. If insufficient data was taken, a "failure" would be noted and a device which in fact did satisfy the functional requirements, would be considered to have failed.

Acceptance criteria used in conjunction with analytical qualification of equipment are usually based on material strength properties or a change in a critical dimension. Often acceptance criteria are not clearly stated in the reports reviewed or insufficient detail is provided to permit the reader to evaluate the physical significance of the acceptance criteria used in analytical equipment qualification programs.

Recommendation

Justification of the acceptance criteria should be included in the test and analysis procedures. This would limit the number of retests and reinterpretation of functional requirements. Anyone who writes or reviews test procedures should be responsible for this action.

2.3 Response Spectrum Margins

Specification of margins added to the RRS (Required Response Spectrum) are rarely given. This issue is complicated by the fact, that several individuals in different organizations may contribute to compound the final margin. It would be highly desirable to maintain a record of the margin accumulated, in order to avoid unnecessary conservatism, although it is recognized that this would be difficult. Since the final result is conservative, no modification is required for the current procedure. However, whether or not the 10% margin specified by IEEE 323-1974 has or has not been included in the RRS is also usually not specified. This leaves an unacceptable ambiguity.

During the development of the RRS to be used in a given test specification, a complete record should be maintained on all adjustments or enveloping which adds conservatism to the final RRS. This information should be included in the test specification. Part of this process should include the 10% margin specified by IEEE 323-1974. In the event that the latter adjustment is not specifically stated as having been included in the RRS, then the test organization should automatically add 10% to the given RRS curve.

3.0 DEMONSTRATION OF ADEQUATE METHODOLOGY

The present program has defined a number of areas where current procedures and methodology are considered to be adequate. These procedures are recognized by the NRC and the industry in general as acceptable. Additional studies in this program and other recent research have shown the applicability of these procedures. Some examples are given here to emphasize their status as acceptable.

3.1 Dynamic Load Combinations

Equipment installed in a nuclear power plant is designed to resist a number of dynamic loading conditions. These include the earthquake loads, loss-of-coolant accident (LOCA) and safety-relief valve discharge (SRV). The method of combining these loads for linear models is generally carried out using one of three methods [8]:

1. Combine by the Square-Root-Sum-of-Squares (SRSS) Method.
2. Combine Absolutely (AS).
3. Combine on a Time-History Basis.

The current program and Kennedy [8] have shown that for statistically independent signals the SRSS method results in an acceptable method of combination. Figures 3.1-1 and 3.1-2 show the horizontal input response spectra and power-spectra for tests performed on an electrical rack during an earlier task of this program [2]. The earthquake signal included excitation from 1 to 33 Hz while energy for an SRV (Safety Relief Valve) discharge was concentrated from 30 to 60 Hz. The response spectrum for the individual events were combined using a SRSS method and compared to a response spectrum for a time-history combination, and found to be favorable. This was repeated for signals with similar frequency content with the same results. When considering PSD's (Power Spectral Density), Figure 3.1-2, the two PSD's are summed directly, corresponding to an SRSS combination on response spectrum.

As noted by Kennedy [8] when the signals are correlated, the SRSS method of combination of response spectrum can result in a nonconservative result. For this case it is necessary to combine the results on an absolute sum or time history bases. It should also be noted that the SRSS and AS combination procedures are applicable to

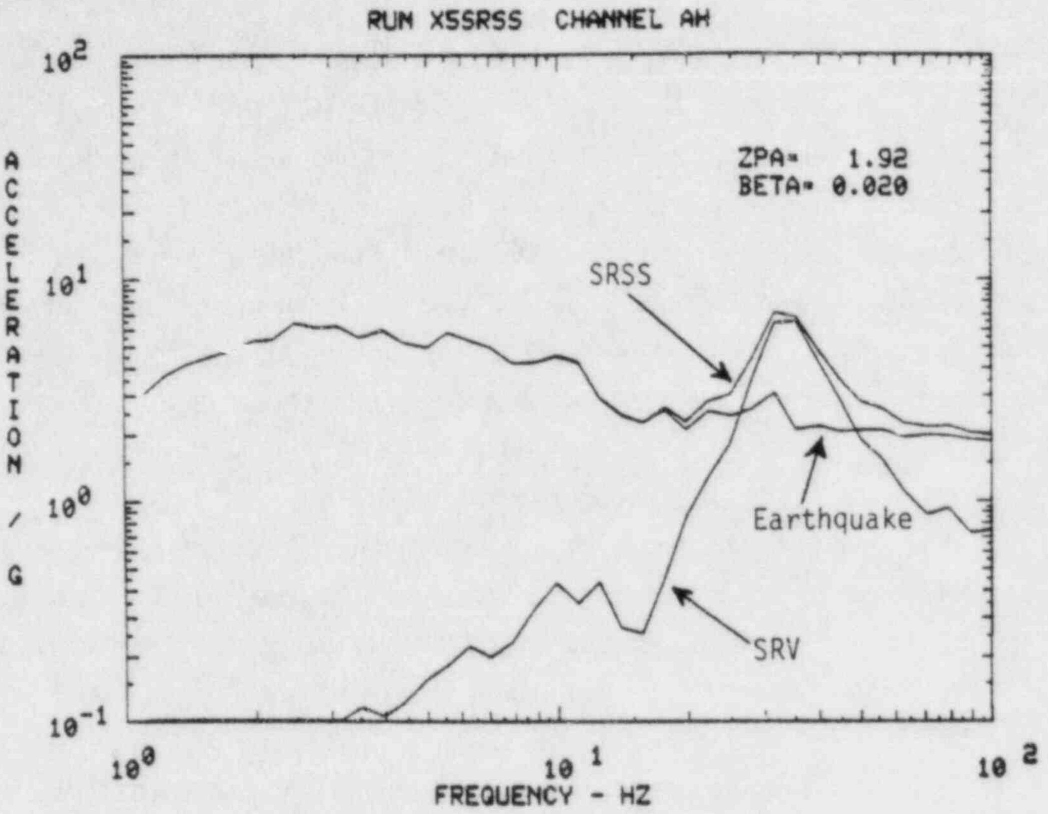


Figure 3.1-1 SRSS of Response Spectrum for Earthquake and SRV

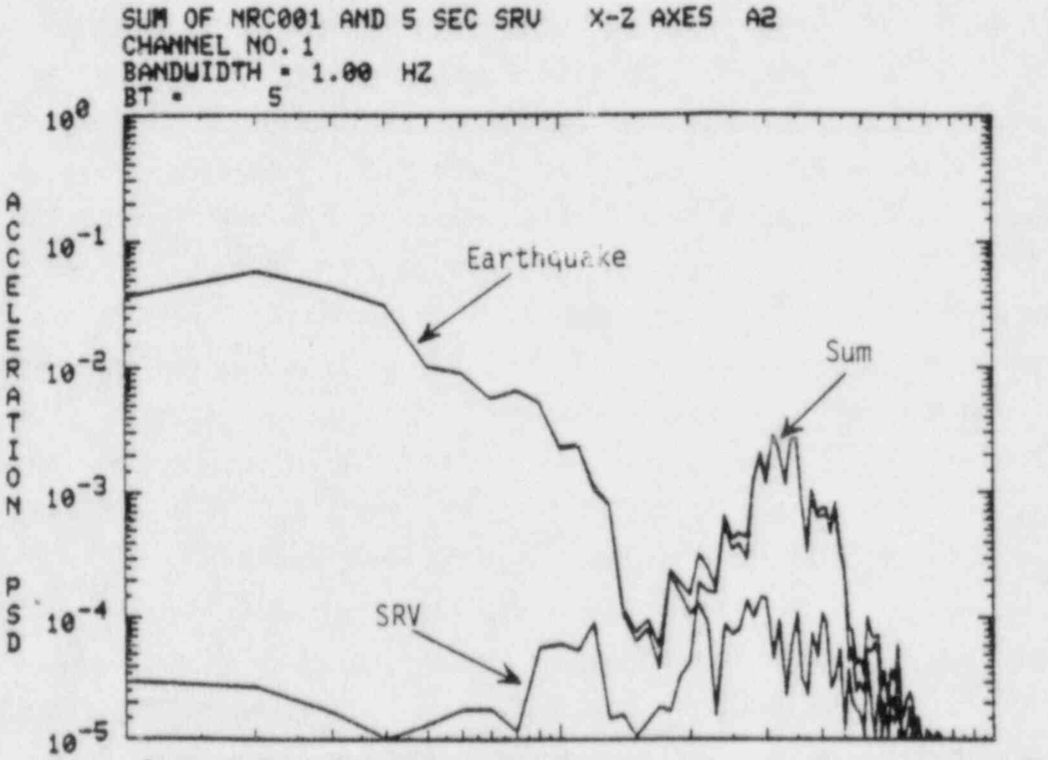


Figure 3.1-2 Sum of Power Spectra for Earthquake and SRV

linear systems. For nonlinear systems it is necessary to consider a relatively expensive time history solution.

The requirements for load combination may change significantly as a result of the NRC program with Lawrence Livermore National Laboratory on load combinations. Preliminary results indicate that there is a very low probability of simultaneous occurrence of the earthquake, SRV, and LOCA dynamic loads. Pending the results of this study the requirements remain that these loads must be combined.

Recommendations

1. The NRC should continue to recognize the SRSS method of load combination for uncorrelated loads.
2. The direct sum of PSDs should be recognized as equivalent to the SRSS method for combination of response spectra.

3.2 Synthesis of Damping

In the seismic analysis of equipment and structures the analytical models include a mechanism of energy dissipation, which is generally referred to as damping. Current procedures usually assume a uniform "equivalent viscous damping" (examples of which are given in NRC Regulatory Guide 1.61) which depends on the level of excitation. Generally when damping is discussed the inferred mechanism is viscous, i.e., the damping force is proportional to velocity. Analysts have long recognized that the use of this damping mechanism is a mathematical convenience rather than a precise description of the energy dissipation mechanism in a structure. This model of damping has persisted, for it provides reasonable results that can be economically derived.

The assumption of uniform minimum damping does not take into account higher damping of components within the model, and often results in extremely conservative analysis. A number of approaches have been developed which take into account multiple damping values. A recent review by Winkel and Julyk [9] has looked at a number of these procedures. Results indicate that the weighted energy approach is the best available method for accounting for nonuniform damping. Similar results are evident in previous studies of aerospace type structures [1].

Analytical approximation of the complex nature of damping in real structures is difficult even when considering uniform damping. The values used are often based on low level testing which is usually conservative. Analysts tend to use these experimentally determined values as precise numbers without evaluating the sensitivity of the structural response to a range of damping. Nonuniform damping is an additional procedure which attempts to provide a more realistic approximation of the physical structure.

Recommendations

1. Based on the results of Reference [9] the weighted energy approach should be considered when using nonuniform damping.
2. Current recommendations (Regulatory Guide 1.61) for uniform damping often produce overly conservative results. Additional test programs should be supported by the NRC to obtain more realistic values. These tests should consider as a minimum:
    a) Level of excitation.
    b) Type of excitation.
    c) Influence of boundary conditions.
    d) Methods used to calculate damping.
    e) Type of structure.

3.3 Degree of Model Complexity and Validation of Analytical Models

Qualification of equipment for use in nuclear power plants can be done either by testing, by analysis, or by combined testing/analytical procedures. Analytical qualification is usually performed on equipment which is too large to test or where performance is primarily a function of structural integrity. An analytical model of the equipment to be qualified is developed, in most cases using finite element methods (FEM), from which the dynamic characteristics of the equipment can be estimated. Using these dynamic charateristics: modal frequencies, shapes, and masses, the structural response of the model can be predicted for a postulated seismic event using either a time history or modal superposition approach. The accuracy of most analytical models is dependent upon a number of factors including: degrees of freedom present, FEM elements used to model the structural system (i.e., rods, beam, solids, plates, etc.), mass distribution, dimensional accuracy, and boundary conditions. The analysis can either be linear or nonlinear, depending upon the nature of the structure being modeled.

Figure 3.3-1 shows a FEM model of an electrical rack used during a testing phase of this program. The rack was subjected to a number of structural identification and qualification tests. Results of these tests were compared to the 265 node FEM model of the rack. It was determined that using standard engineering practice, a reasonably accurate model could be developed from blueprints of the rack. The geometry, stiffness, and mass distribution could be modeled accurately. A major difficulty was encountered in modeling the boundary conditions, which had a significant effect on the bending and torsional modes of the rack. It is felt that accurate modeling of the boundary conditions is critical to the accurate prediction of the as-tested, or in-plant dynamic characteristics of any item of equipment.

Qualification of equipment purely by analysis is being viewed as requiring increasing justification. This results from a variety of uncertainties which enter the process of synthesizing analytical models. Uncertainties in materials, boundary conditions, and the presence of various sources of significant nonlinearities are all of concern. Therefore, verification of analyses by some kind of laboratory, or inplant testing is becoming commonplace unless such uncertainties are accounted for by adequate margins. As a minimum, the verification of mode shapes and natural frequencies is necessary to understand the response of the equipment.

There has also developed a quite different type of combined analysis and test qualification methodology that poses a whole new series of difficulties. In-situ testing refers to the acquisition of equipment dynamic data by tests performed directly on equipment that is installed in the plant. This method has been prompted by the nonfeasibility of removing the equipment from the operating plant for testing. Generally, the technique employs some means of generating transfer function data between many points on the equipment while fixed in place in the plant. The experimental data are used to generate the modal mass and stiffness properties which form the ingredients of a base-fixed analytical model (i.e., Figure 3.3-2). This model must then be transformed to a moving base model, which can be used to predict

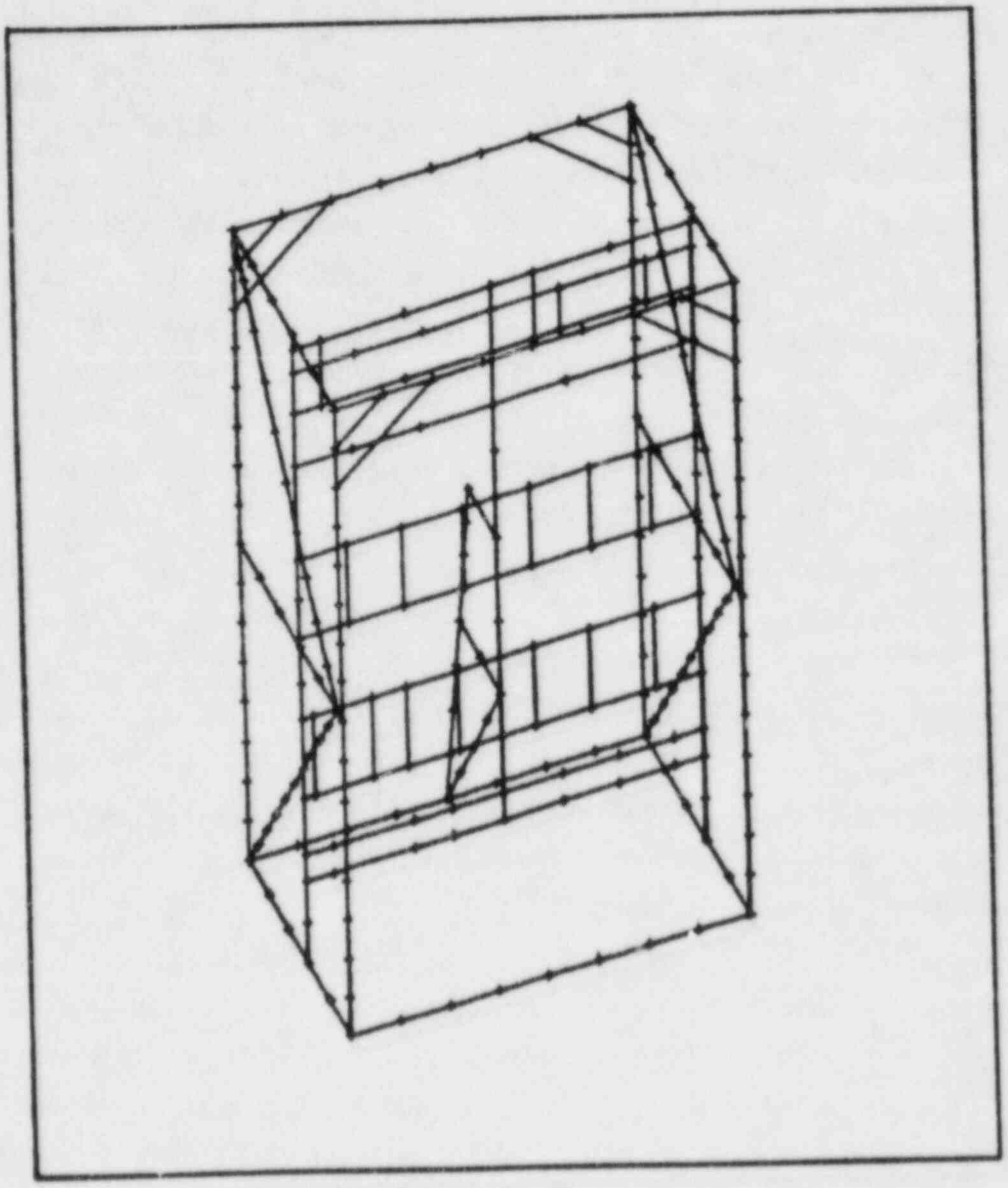


Figure 3.3-1 Finite Element Model of Specimen

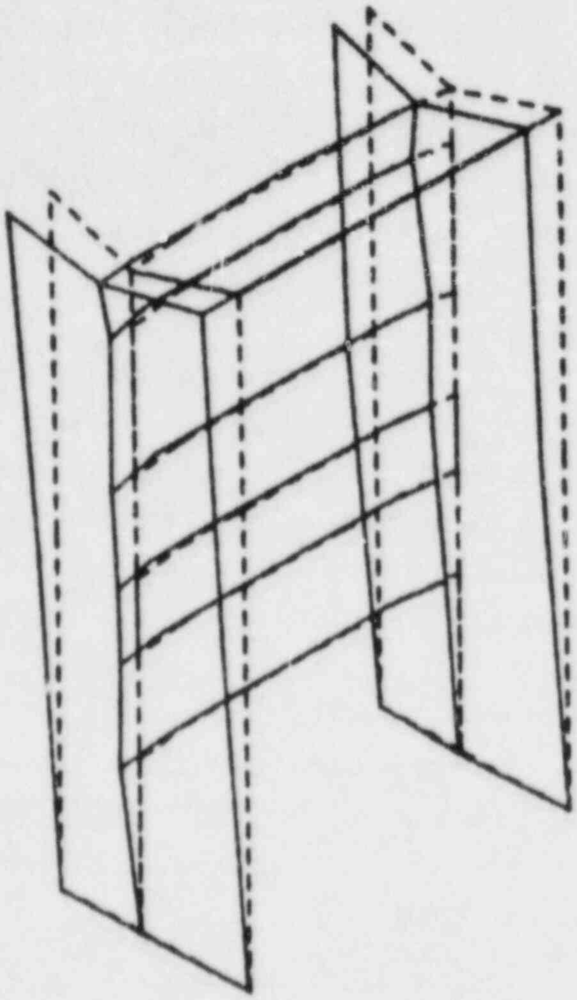


Figure 3.3-2 In Situ Model Mode 1, 11.6 Hz
Side/Side Bending of Frame

responses to seismic excitation by any of the usual analytical methods. The methodology requires utmost care in order to assure adequate results. Unruh et al. [5] have reported a study in which the process has been applied to a cantilever beam and a typical electrical rack. Results from both the simple beam model and electrical rack compared favorably with experimental results when the boundary conditions were accounted for [2]. For the electrical rack shown in Figure 3.3-2, 50 nodes were used to acquire the in-situ data.

In both independent analytical and in-situ models it was found that standard engineering practices (see page 35) resulted in adequate models. The major source of error was in the determination of the boundary conditions. It should also be noted that the determination of functionality using analytical models should be restricted to structural integrity. Mechanical and electrical functionality are difficult to determine using purely analytical procedures.

Recommendations

1. Analytical procedures based on sound engineering judgement should continue to be used in the qualification of equipment whose functionality is based on structural integrity or mechanical deflections. Furthermore, analysis combined with verification tests on subcomponents should be used on very large assemblies.
2. Justification of the appropriate boundary conditions must be included in the analytical report.
3. Some form of experimental verification should be required for all qualification by analysis unless justification for not doing so is given. This may be required only on subcomponents where the system is very large.

4.0 NEW METHODOLOGY

As the result of work in this program, a number of new procedures have been developed to supplement current qualification procedures. These procedures have been shown to produce satisfactory results and are appropriate for consideration. They are intended to be used as aids in providing further assurance that existing qualification requirements are satisfied, or for solving certain problems for which methodology previously did not exist.

4.1 Response/Power Spectrum Transformation

The response spectrum has typically been used since the 1930's to estimate the peak response of structures to an earthquake motion. Inherently, it is also used as a parameter to describe the earthquake motion itself, through its effects on a single degree of freedom oscillator. Thus, its properties as an earthquake descriptive parameter must be understood carefully for its use in seismic qualification of equipment, whether done by test or by analysis. Earthquake motions can also be described similarly by power spectral density functions, which provide a description of the energy content of the motion itself, without any reference to the effects of the motion on a structure. Although the use of either parameter for the description of an earthquake is analogous, it is often more useful to use one or the other because of its specific mathematical properties.

The response spectrum is recognized to represent a plot of the peak response of a series of single degree of freedom oscillators with specified natural frequencies, when all oscillators include the same damping, and their bases are subject to the same earthquake motion. Thus, the plot implicitly becomes a nonunique description of the motion that produced the responses. Furthermore, it is recognized that energy is present in the excitation only at those frequencies where amplification over the zero period acceleration (ZPA) occurs for the acceleration response spectrum.

A power spectral density (PSD) expresses the mean square energy of a given time history as a function of frequency. A relationship between the response power spectral density $G_y(f)$ at an elevated point y and the excitation power spectral density $G_x(f)$ at point x of a linear system subject to a stationary random process can be determined using

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

In view of the fact that most earthquake data is developed in terms of response spectra, and yet it is very useful to use power spectra for some purposes, it becomes desirable to consider a transformation between response and power spectra and vice versa. Such a transformation has recently been developed by several investigators [2]. Figures 4.1-1 and 4.1-2 show a constant bandwidth, 0.2 Hz, time history PSD and a 1/6 octave transformed PSD, from the response spectrum, for a horizontal component of the El Centro 1940 earthquake. The PSD's for the two signals compare favorably, considering the variation in analysis points. The reverse transformation, PSD to response spectrum, has also been shown to produce favorable results [2]. This relationship has been used to examine several areas of the qualification procedure.

The first area is the development of elevated response spectra for testing of devices. When new components are to be located on a previously qualified rack, rather than retest the entire electrical rack, it is often possible to retest only new components to be placed on the rack. If a transfer function, $H_{xy}(f)$, between the base and the location in question is available, the elevated response spectrum can be developed. The base response spectrum is transformed to a PSD and used in equation (4-1) to develop the elevated location PSD. This can then be transformed to obtain a required response spectrum for use in a device testing program. Unruh and Kana [10] describe a second area where this procedure can be used to account for overtesting, when inputs for device tests are measured at response locations on a system that has been subject to excessive excitation. A six-step approach is described using the transformation procedure. A final area of use is in the development of damping-consistent response spectra. Often the required response spectra are given at a number of damping values. The test lab is then required to envelope at one value for the test, and then calculate test response spectra for the other values of damping. By using the transformation procedure it has been found that in many cases

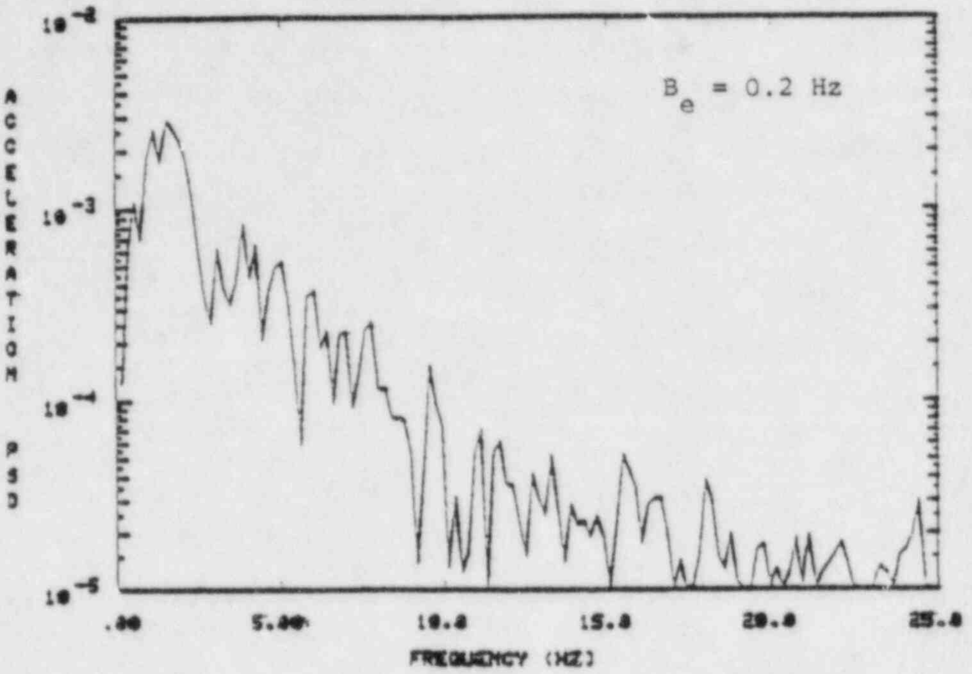


Figure 4.1-1 Computed PSD for El Centro 1940 SM

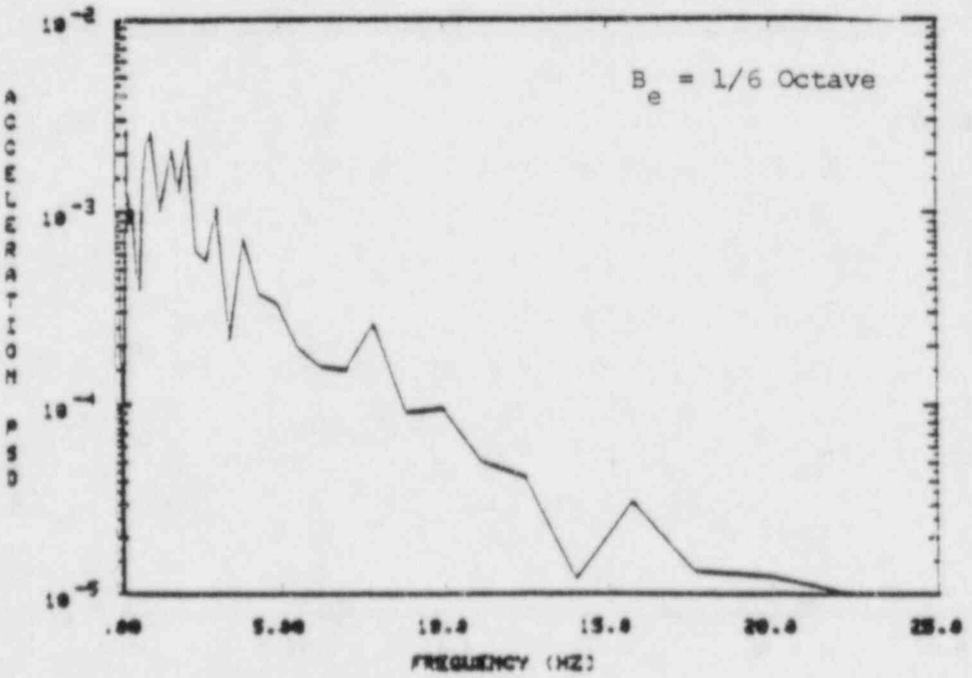


Figure 4.1-2 Transformed PSD for El Centro 1940 SM

(even for RG 1.60) the various curves are not consistent, i.e., cannot be derived from one another. Individual curves will dominate for different frequency ranges. Thus, if a test response spectrum envelopes a required response spectrum at a given damping value, it does not imply that it will necessarily envelope at all damping values.

Recommendations

1. The response/power spectrum transformation should be approved by the NRC as an aid to answer certain questions described above.
2. If multiple damping response spectra are specified, assurances should be made, by the specifying oranization, that they are consistent.

4.2 Waveform Parameters

In the qualification of nuclear power plant equipment it is often required to synthesize artificial time histories which represent earthquake excitation at either ground level, or some elevated level of a structure. For equipment qualification purposes, IEEE 344-1975 includes several different recommended methods for generation of simulated earthquake environments. The major requirement is that the excitation time history should conservatively simulate the strong motion portion of a postulated earthquake event. As a part of this program [2,4], a study of six earthquakes was performed to determine parameters which could be used to assure that this requirement was satisfied. The criteria shown in table 4.1 resulted from the study.

TABLE 4.1 CRITERIA FOR EARTHQUAKE SIMULATION

General Characteristics of the Motion
Strong Motion Portion
Frequency Content
Stationarity
Coherence
Amplitude Probability Density

The general motion of an earthquake can be considered to be a random acceleration signal whose peak amplitude is modulated by a function with periods of build-up, hold and decay. During the hold or strong motion portion the signal is assumed to be stationary, an important hypothesis for both test and analysis methodology. For this study the strong motion portion was defined as that where the time interval RMS levels were greater than 1.25 times the overall RMS levels. The general characteristics of the simulated earthquake signal can be seen in the time history in Figure 4.2-1.

Frequency content of a waveform can readily be shown by use of a PSD, and somewhat less directly by the use of a response spectrum. Of course however, the test specification is usually given in the form of an RRS. The RRS to PSD transformation can readily be applied to observe frequency content directly without including its effects on a spring mass system.

Time interval PSD's, shown in Figure 4.2-2, were used to look at the stationarity of the strong motion portion of the earthquake and test signals. The maximum, $G(f)_{max}$, and minimum, $G(f)_{min}$, values of the time interval PSD during the strong motion were used to provide an indication of the stationarity of the signal. For the resolution and number of statistical samples shown in Figure 4.2-2 it was found that for adequate stationarity one should have

$$G_{max}/G_o < 2.8$$
$$G_{min}/G_o > 0.17.$$

For this study coherence was used to determine the appropriate statistical independence of the earthquake signals. Typically the coherence was no more than 0.3 for most combinations of horizontal and vertical components of ground level motion. A typical test signal result for the electrical rack test is shown in Figure 4.2-3. Both the earthquake signals and the test signals can be considered to be independent.

A final consideration was the amplitude probability density which expresses implicitly the percentage of the time that the amplitude is within a given interval during the strong motion. This is obviously

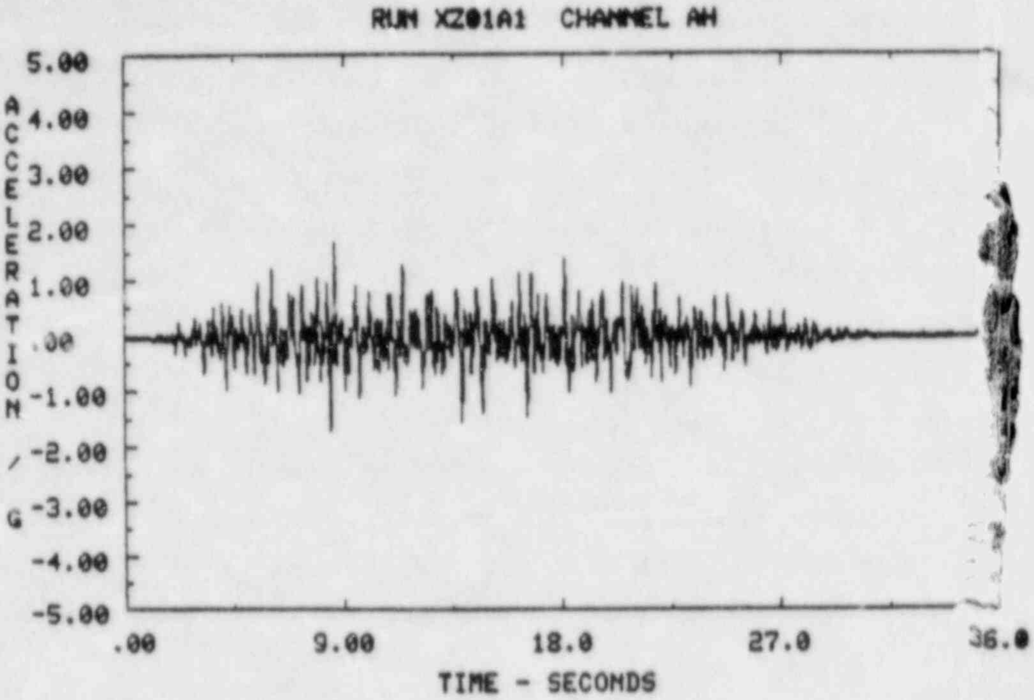


Figure 4.2-1 Horizontal Excitation Time History for Run 001

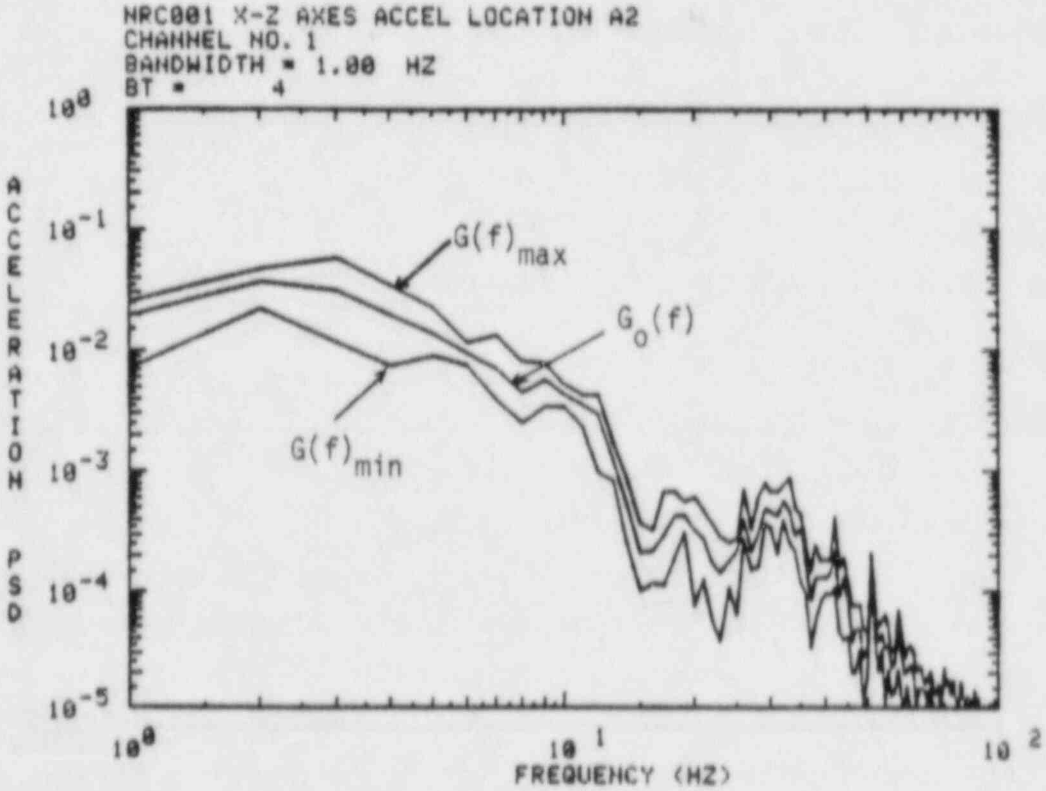


Figure 4.2-2 Stationarity for Horizontal Run 001 with BT = 4

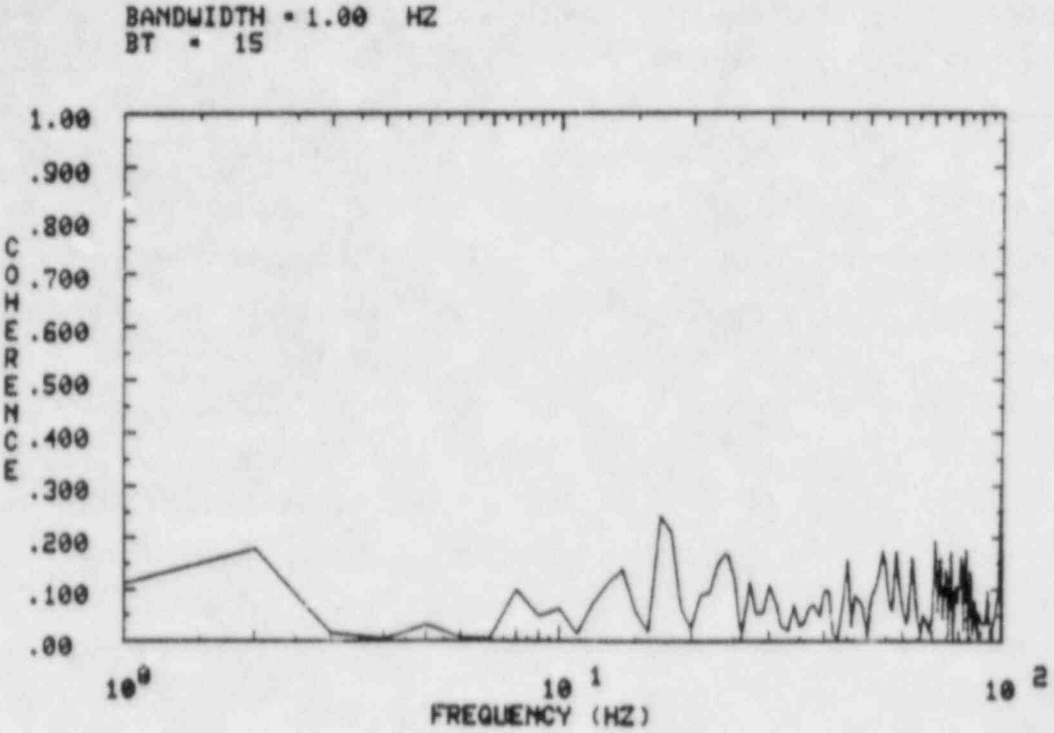


Figure 4.2-3 Coherence Between Horizontal and Vertical Run 001

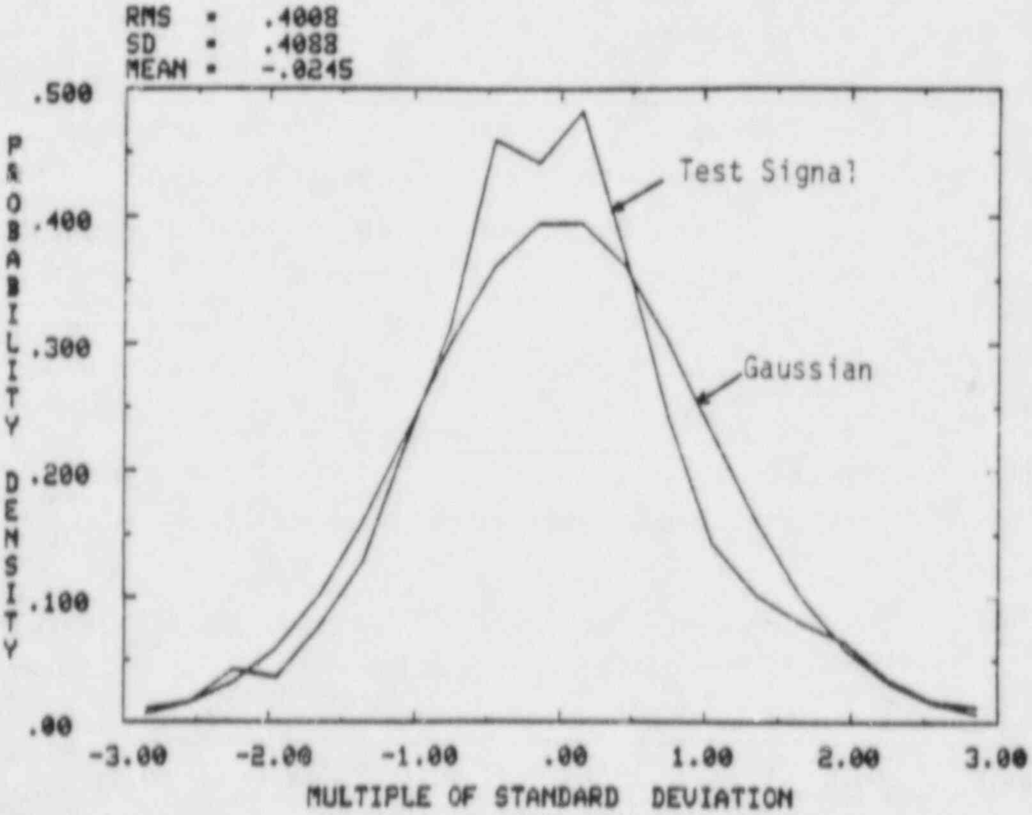


Figure 4.2-4 Amplitude Probability Density for Horizontal Run 001

important for fatigue and other repeated cycle failure considerations. When compared to a standard Gaussian distribution, it was found that the earthquake's distribution was more centrally concentrated with resulting peak to RMS ratios greater than three. Test signal results (Figure 4.2-4) were similar.

Resolution bandwidth, number of data samples per block (time interval), statistical degrees of freedom, etc., are all statistical analysis parameters that are listed on the various preceding figures. These parameters describe the degree of statistical accuracy, i.e., variability, that can be expected from a stationary random process. The strong motion portion of earthquakes are typically relatively short in duration. With a resolution bandwidth of about 1 Hz (a reasonable value for lightly damped structures), it is apparent that relatively low numbers of sample averages must be contended with. Nevertheless, for each presentation of such data, it is important to state what the analysis parameters are, so that the appropriate statistical variation of the results can be kept in perspective.

Recommendations

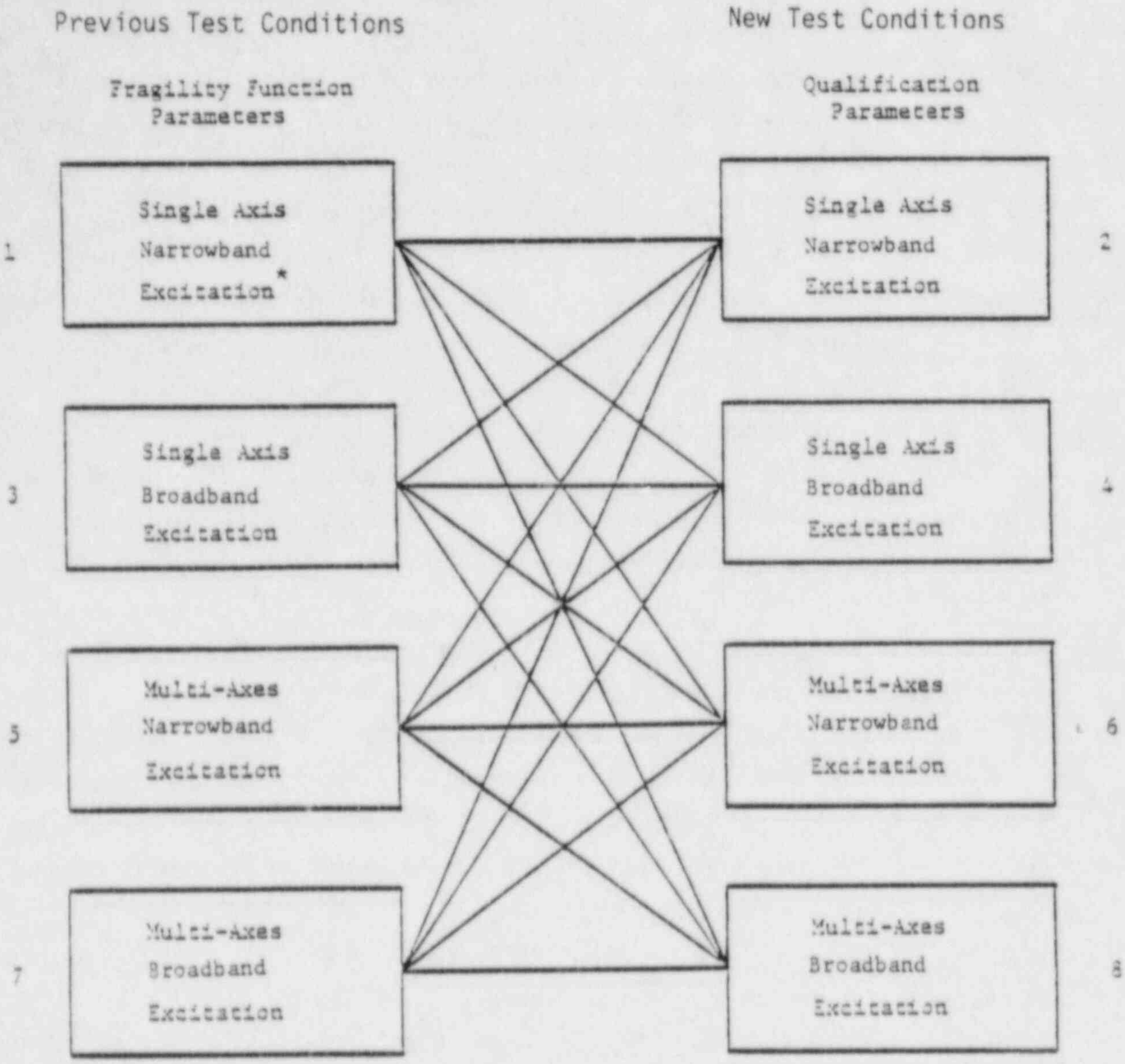
1. The following parameters should be considered when generating simulations for the strong motion of earthquake signals.
   a) Frequency content
   b) Stationarity
   c) Coherence (less than 0.3 for ground level motion)
   d) Amplitude probability density (Gaussian)
2. A standardized definition of the strong motion portion of the earthquake signal should be established in a suitable NRC Regulatory Guide. The definition on page 21 (or a similar definition) is appropriate.
3. All presentation of this data should include the statistical analysis parameters used (resolution bandwidth, data samples per block, and/or statistical degrees of freedom).

4.3 Correlation of Test Methodologies

One of the most difficult problems that has arisen in recent equipment qualification efforts results from the change in requirements from the 1971 to the 1975 versions of IEEE 344. The earlier tests were relatively simple to conduct (i.e., test types 1-2 in Figure 4.3-1). However after 1975, multiaxis and broadband tests have become the norm. The obvious question is, do the earlier tests satisfy the more recent criteria? If not, of course, much earlier equipment would need to be requalified. Work in this program has lead to the development of a method of comparing various test types by means of a vibration equivalence concept [3]. Typically, equivalences of various types of vibration waveforms are established on the basis of some form of assumed failure mechanism. In nuclear plant equipment, a variety of functional failure mechanisms are possible. Therefore, for this purpose, the concept of vibration equivalence was generalized to include an arbitrary type of failure or malfunction, that can always be established by measuring excitation conditions denoted as the fragility levels.

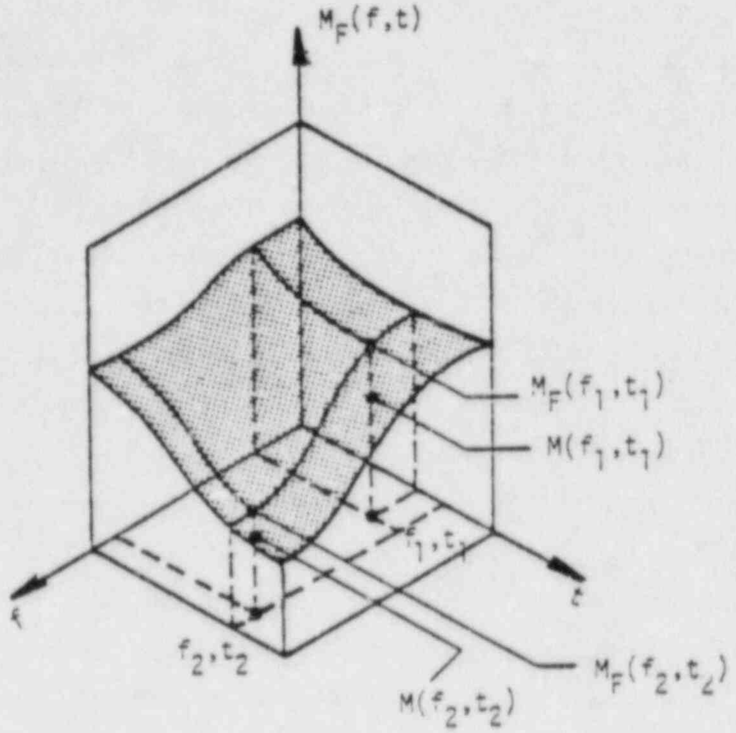
The general procedure for this correlation includes the use of a fragility function and damage fragility ratio [3]. However, the procedure outlined herein includes some additional provisions not included in the original development. The concept is shown briefly in Figure 4.3-2. In general, the fragility function for dynamic environments is known to be a surface whose magnitude is given as a function of frequency and time. At any pair of frequency and time coordinates the fragility magnitude lies on the surface. The basis of equivalence requires that the damage fragility ratio, which is the ratio of an actual given magnitude $M(f,t)$ to that for the fragility $M_F(f,t)$ at the same coordinates, must be equal for the different sets of frequency and time coordinates. This is indicated by the equation in Figure 4.3-2. Thus, different types of test environments can be compared according to their damage fragility ratios.

Although this procedure for correlation includes the use of a fragility function and damage fragility ratio, the measurement or analytical determination of an exact fragility function (which is useful information for its own sake), probably is not necessary for the purpose of the test correlation. For that matter, exact fragility information on the equipment is very likely not available. Therefore, the procedure developed includes the establishment of an approximate, but acceptable, lower bound fragility function, which is formed by the earlier qualification test excitation conditions. Hopefully, this approach



*Includes sinusoidal excitation

Figure 4.3-1 Possible Combinations of Fragility Function and Qualification Parameters



$$M(f_1,t_1)/M_F(f_1,t_1) = M(f_2,t_2)/M_F(f_2,t_2)$$

Figure 4.3-2 Basis for Damage Fragility Ratio allows the correlation to be accomplished. The chances of success depend very much on the relative severity of the two sets of criteria being compared. Should this approximate procedure provide negative results, acquisition of more accurate fragility information would be necessary to provide a more definite test correlation.

Thus, definition of the approximate fragility function from the earlier qualification level, and comparison of the newer test levels to show that they are lower in magnitude, constitutes the fundamental approach to test correlation. The earlier qualification level is that which was previously used to qualify the equipment under evaluation. This level may have been measured in terms of a magnitude of a sine wave excitation, a test response spectrum for random excitation, or some other magnitude parameter. Hence, a variety of parameters or their combinations may need to be compared. Figure 4.3-1 shows some possible combinations of types of tests that have been used to qualify equipment in the past, and may be required at present. In the earlier tests the following factors may have been used to define the excitation conditions, and therefore become parameters for fragility measurement:

1) Axis of excitation - single or multiple
2) Magnitude - peak or RMS amplitude, RRS/TRS, or PSD levels
3) Frequency content - narrowband, including sine excitation, or broadband.

For the conditions that are connected by horizontal lines in Figure 4.3-1, the procedure for calculating the damage fragility ratio (see Figure 4.3-2), can be directly applied. This is the case where the excitation parameters used to derive the fragility function are similar in nature (with respect to axes and frequency content) to the qualification requirement parameters. Those connected with left to right upward sloping lines represent a simplification of the qualification excitation over the fragility function excitation. The procedures given in Section 3.0 of Reference [3] can be used to derive the damage fragility ratio for these cases. The final combination (left to right downward sloping lines), whose qualification excitations are more complex than the fragility function excitation, may require extrapolation when interaction is found to be important (see Section 4.0 of Reference [3]).

Table 4.2 provides some more detail concerning the procedure for determining whether equipment, which was subjected to a previous narrowband qualification test, is still qualified under a new broadband test specification. This type of comparison is most likely to be required for comparing older (Pre-1975) to newer (Post-1975) qualification data. This procedure assumes that a response spectrum or power spectrum can usually be developed as the parameter for which comparisons are made.

TABLE 4.2 PROCEDURE FOR CHANGE FROM NARROWBAND OLD TO BROADBAND NEW QUALIFICATION TEST

1. Transform the old qualification input to a TRS or a PSD.
2. Make a conservative assumption about the location of the critical item or location of maximum response on the equipment.
3. Obtain transfer functions for that location (may need to perform in-situ test or analysis).
4. Check if multiple modes are present in energy range of new RRS.
5. Develop weighting factors for multiple modes from transformed PSD of new RRS.
6. Calculate interaction correction factor α_1.
7. Calculate cross-coupling correction factor α_2 (e.g., 1/1.2) to allow for potential cross-coupling.
8. Calculate corrected, old TRS and compare with new RRS.
9. Consider demonstration of functionality for previous test and verify whether excitation frequencies are similarly applied in new test.
10. Repeat procedure for each axis.

As an example of the procedure, consider the old test as having been performed with the 0.5 g slowly swept sine wave, whose envelope TRS is shown for 5% damping in Figure 4.3-3. At this point it should be recognized that such consideration of the envelope response spectrum for

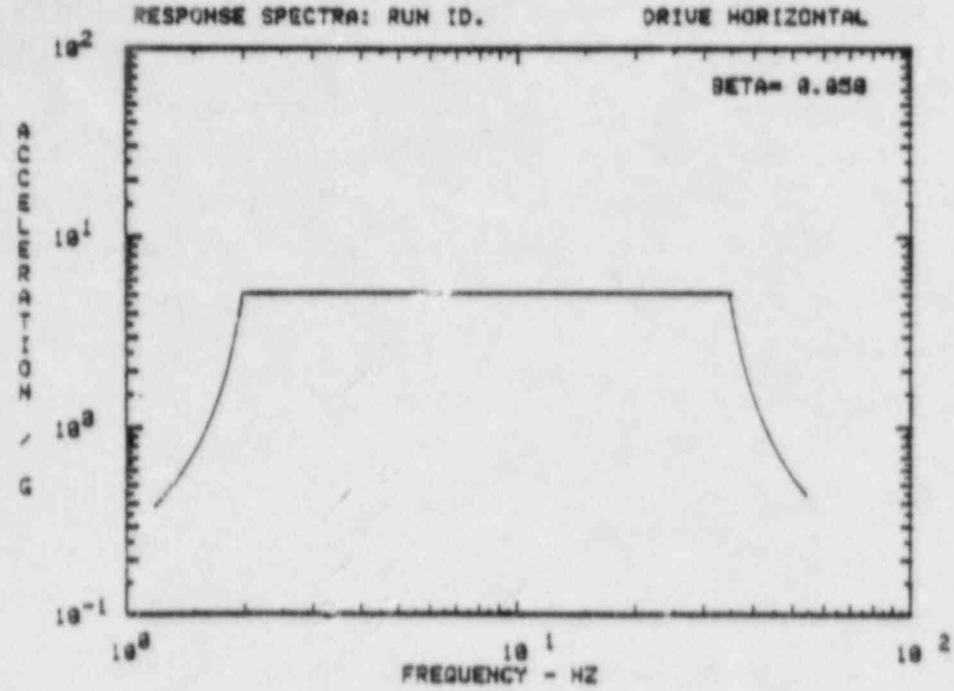


Figure 4.3-3 Envelope for Slowly Swept Sine TRS with 0.5 g ZPA

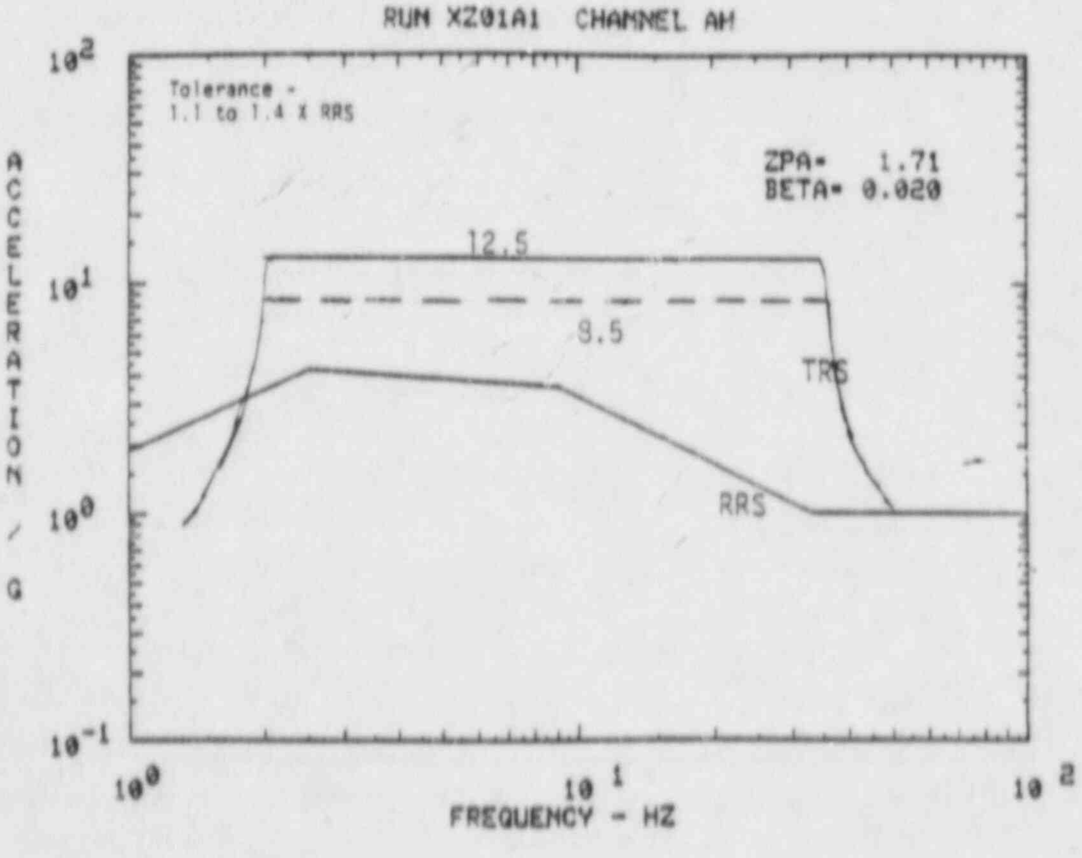


Figure 4.3-4 TRS Envelope of RRS for Run 001

a swept sine test is strictly prohibited by IEEE 344-1975. However, the reason is that potential interaction of multiple modes is otherwise not allowed for. Here we will include a correction factor so that potential interaction is approximately accounted for.

The same data for the previous test is presented for 2% damping in Figure 4.3-4, where the new broadband test RRS is also shown. At face value, it would look like the new qualification is still valid since the RRS falls below the swept sine TRS at 12.5 g. However as mentioned above, this TRS must be adjusted for interaction of modes in the equipment by a correction factor α_1 and for cross-coupling by a correction factor α_2. It is assumed that the transfer function given in Figure 4.3-5 is representative of the location of the critical item. Two modes, 23 and 38 Hz, are present. Using the amplitude of the transfer function, 28 and 25 respectively, and the weighting factors, 1 and 13/20 respectively, which are obtained from the PSD at the respective frequencies (Figure 4.3-6), a total correction factor can be obtained as:

$$\alpha = \alpha_1 \alpha_2 = \left[\frac{(28^2 (1) + 23^2 (13/20))^{1/2}}{28} \right] \left(\frac{1}{1.2}\right) = 0.68$$

The interaction weighting factors are the relative values of the PSD at the various frequencies, assuming 1.0 to be the largest value. This approach allows for the use of information about the energy content of the new test requirements to be included in calculating the interaction factor α_1. The old TRS is then modified by multiplying by the interaction correction factor α_1 and the cross-coupling correction factor α_2, and comparing to the new RRS, as shown in Figure 4.3-4. Thus, the original TRS envelope of 12.5 g is reduced to 8.5 g, but still envelopes the new requirement. The item therefore qualifies under the new requirement if operability is satisfied.

To alleviate some of the complexity of this procedure use of a conservatively assumed value of the interaction correction factor α_1 (such as $\alpha_1 = 0.7$) would be very practical, as long as it appeared valid, and indeed allowed a comparison of the tests to be made. Such an approach appears to be quite feasible, and even if it led to an

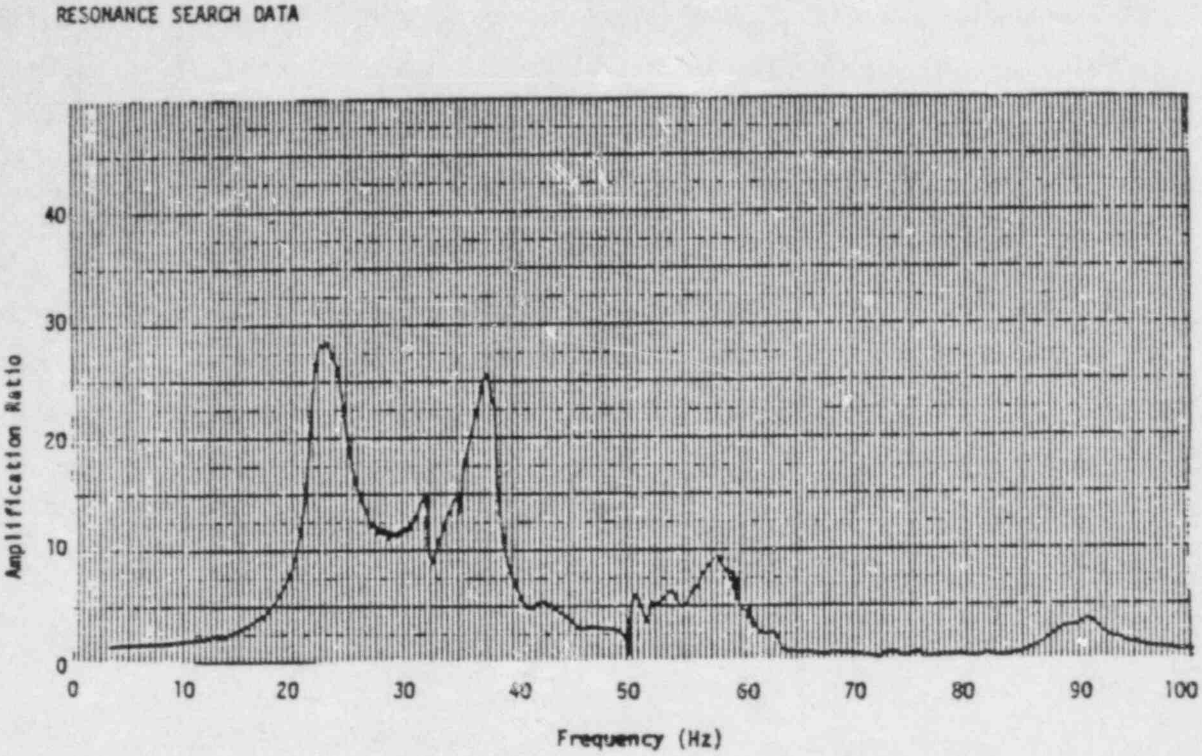


Figure 4.3-5 Instrument Position Transfer Function for Sine Sweep with Fixed Vertical Table for Electrical Rack

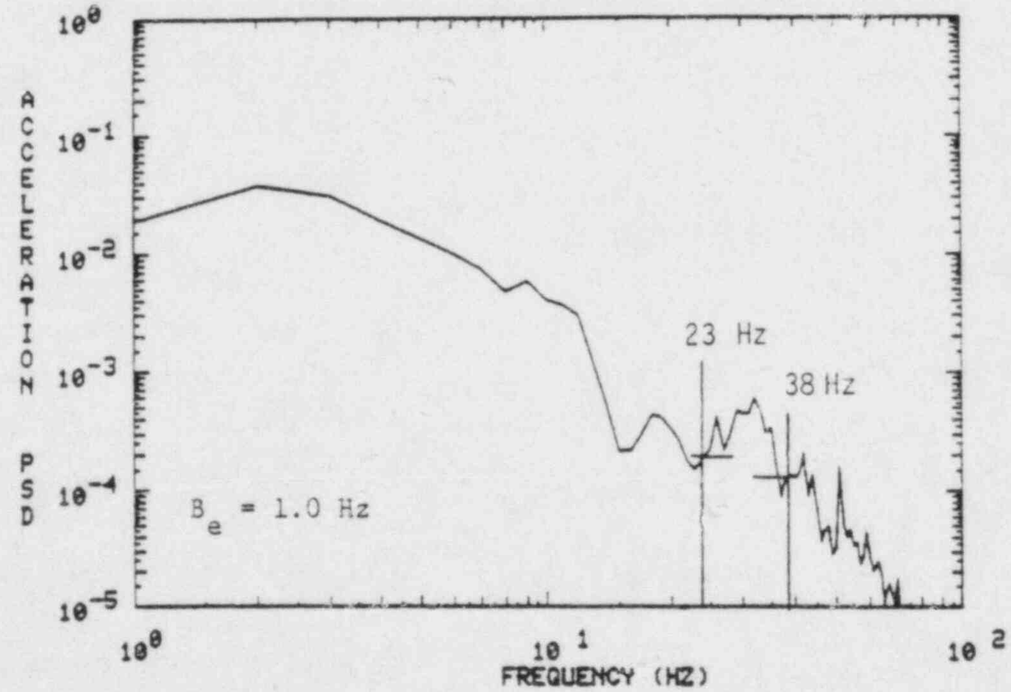


Figure 4.3-6 PSD of Input Motion to Electrical Rack for Run 001

indeterminate comparison, it could be supplemented by the more detailed calculation of a correction factor as outlined in Table 4.2. The value of 1/1.2 for α_2 is simply an educated guess at this point. Both α_1 and α_2 require further developmental work, as will be discussed in Section 6.0.

The operability statement given in step 9 includes verifying that energy is present at the same frequencies for a similar time duration which includes a complete operation cycle in both cases.

Recommendations

1. Test correlation procedures based on fragility concepts should be accepted by all concerned as a standard method of comparing various test procedures.
2. The weighted factor procedure should be used to account for multimode response in narrowband test results. The use of an interaction correction factor of 0.7 may result in a conservative approximation of modal interaction.
3. Consideration should be made in current test programs to obtain fragility related information. It is not the intent to require additional tests for qualification but to provide necessary information (assumed critical location and failure mode, appropriate transfer functions, influence of bandwidth of excitation, etc.) in the event that subsequent requalification is required.
4. A data bank of qualification and fragility information should be established for each equipment category listed in Table 2.1 Preliminary information on this will be provided in Task 4 of this program, and further discussed in Section 6.0 below.

4.4 In-Situ Test/Analysis

Equipment located in current operating plants has been qualified by a variety of procedures most of which preceded the current criteria. Review of those procedures reveal that requalification to newer criteria may be necessary in some cases, and upgrading of equipment to higher stress levels may be appropriate in others. In either case, loss of the equipment from the plant or repurchase of equipment for test purposes is very undesirable, since plant shutdowns or high expenditures for additional equipment may be required. The concept of in-situ testing, whereby a combined in-plant test and subsequent analysis is performed, appears to be an attractive approach to requalification of such equipment [5].

The degree of in-situ test and/or analysis required for a particular component can vary depending on the parameters that describe the functionality of the component. If structural integrity completely assures funtionality, the in-situ test data need only be used to verify natural frequencies and modal parameters of an analytical model used to qualify the component. On the other hand, a functionally-complicated piece of electronic equipment located within an enclosure would need to be retested to determine its qualification. While purchase of the particular component for test purposes may be nominal, the purchase of a completely assembled enclosure for test would most likely be prohibitive. For this particular case in-situ measurements would be necessary to develop the required response spectrum for the particular equipment location. In this manner, subsequent component tests would probably take into account equipment amplification due to its elevated mounting within the enclosure. Several other equipment qualification scenarios are possible depending on the type of equipment.

Modern modal analysis packages employing microprocessor-based Fast Fourier Transform (FFT) analyzers are capable of characterizing a structure by detecting its normal modes of vibration and certain modal properties, i.e., mass, stiffness, damping, mode shape, and frequency characteristics. The open literature available on modal analysis test techniques is quite extensive. The primary physical properties extracted from the modal analysis operation are the structure normal mode frequencies, mode shapes, and the critical damping ratios. While several systems can compute the modal mass, it has been the author's experience that modal mass cannot be determined accurately due to influence of closely spaced modes.

In order to compute the desired transfer functions the modal participation factors of the system must be found. This requires the physical mass matrix of the structure and the modal masses. Two procedures were developed, MASOPT and UMASS, to determine a consistent set of mass parameters [2,5]. Using these results several analytical models were developed and compared to experimental results giving favorable results [2].

A second problem area for in-situ testing is a conflict between the number of nodes used in the model and the number of modes of interest. In modal testing the trend is to select a high number of structural node points at which measurements are to be taken in order to accurately define the normal mode eigenvectors, i.e., mode shapes. The number of node points to accurately describe a mode shape is highly dependent on system geometry; however, for a simple cantilever beam it is not unreasonable to choose four to five points between nodes of the mode. This being the case the number of nodes required to accurately define the R^{th} mode would be on the order of 5R. If such measurements were taken, it can be seen by the data given in Figure 4.4-1 that the system measurements would result in an underdetermined system for the solution of the nodal mass distribution if less than 11 normal modes were recorded. With the emphasis in the seismic area to design structures with a first normal mode resonance beyond 33 Hz, the number of modes within the frequency range of interest could be very few. Thus one can see a conflict in mesurement specification if an overdetermined or underdetermined system of equations are desired for the specification of the nodal masses, i.e., the modal participation factors. The UMASS algorithm can be used for the solution of an undetermined system [2].

Recommendations

1. The use of in-situ testing can reduce the effort required for requalification of equipment. The MASOPT AND UMASS procedures described in Reference [2] have been shown to provide acceptable results. It is recommended that these procedures be accepted for use in in-situ qualfication procedures which include seismic excitations. Any other justifiable procedures for estimating modal participation factors may also be considered.
2. Procedures using in-situ testing should include some evidence of verification of the methodology. This need be established only once.

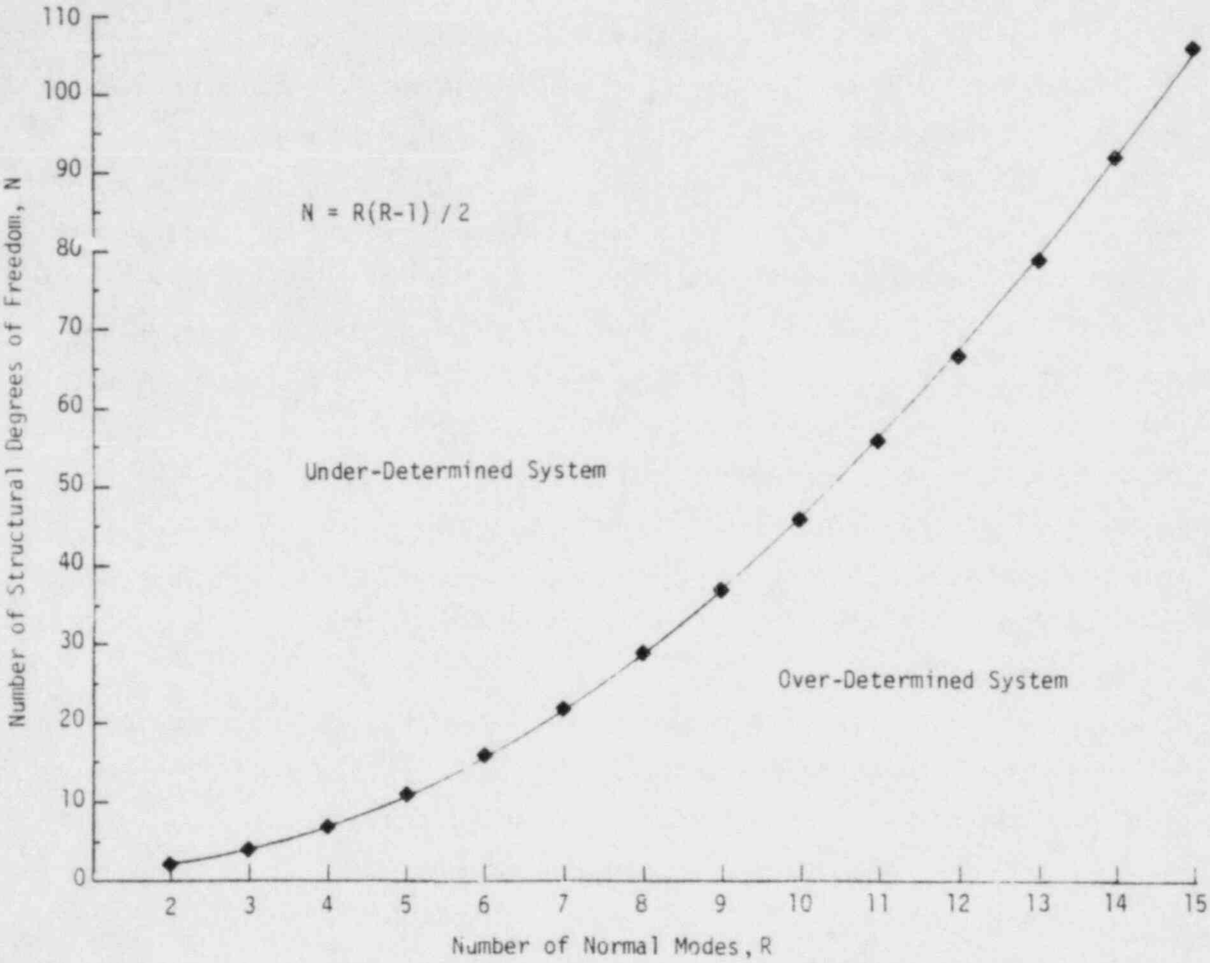


Figure 4.4-1 Relationship Between Structural Degrees of Freedom and Normal Modes for a Well-Defined System

5.0 PROCEDURAL CLARIFICATIONS/MODIFICATIONS

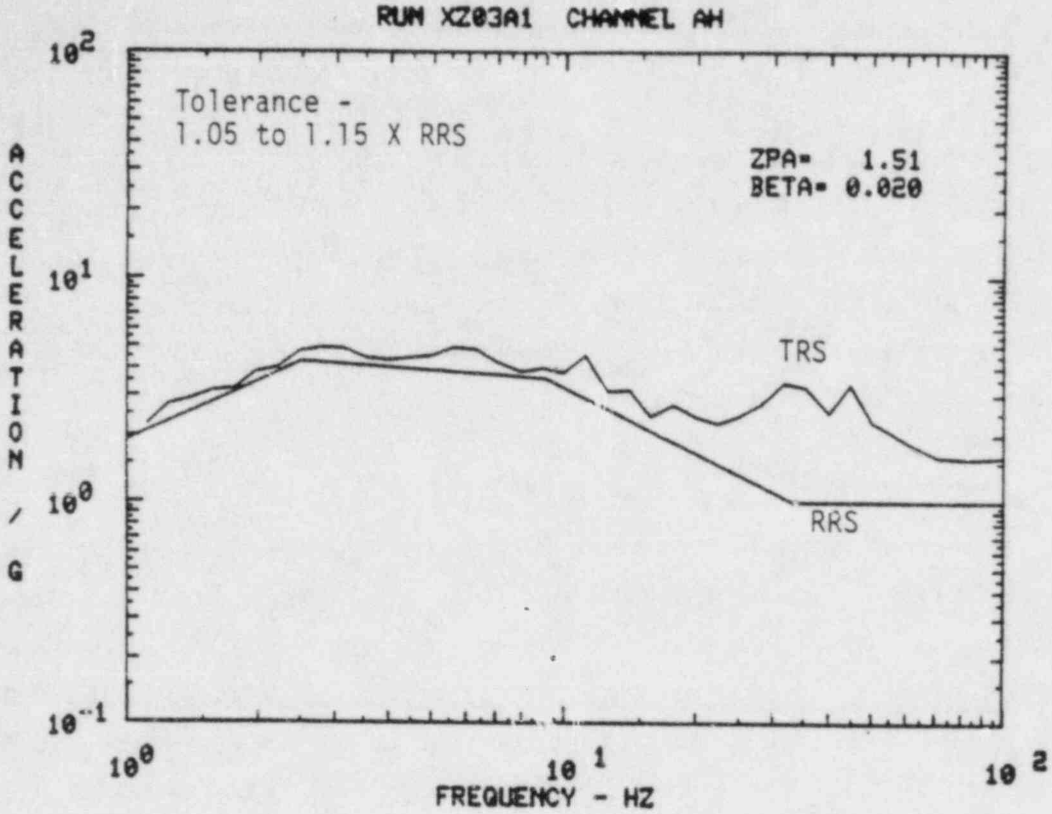
Several technical issues may be considered to be clarifications or modifications of current procedures utilized in qualification. These issues do not incur a basic change in philosophy, but may include the use of some of the new methodologies outlined above for their implementation. The intent of these modifications is to provide a more acccurate or refined analysis or test.

5.1 Waveform Characteristics

Use of correct frequency content in synthesizing qualification time histories for both analysis and test has always been recognized as an important requirement. Furthermore, it has been mentioned that frequency stationarity is another important waveform characteristic. However, the simple specification that a TRS envelope the RRS has been shown [2] to be inadequate for assuring the presence of these characteristics in simulation signals. This inadequacy manifests itself especially in test results where the amplified region of the TRS, which is an indication of the frequency content present, is often confused by the presence of unwanted high ZPA's. Thus, the true frequency content of the time history becomes obscure. Figures 5.1-1 and 5.1-2 give examples of close and more-typical enveloping for a ground level simulation. The data presented in Reference [2] indicated that the frequency content of the TRS in Figure 5.1-2 was inadequate, in spite of the fact that the TRS enveloping of the RRS was quite conservative. Furthermore, no specification on frequency stationarity has been presented in the past.

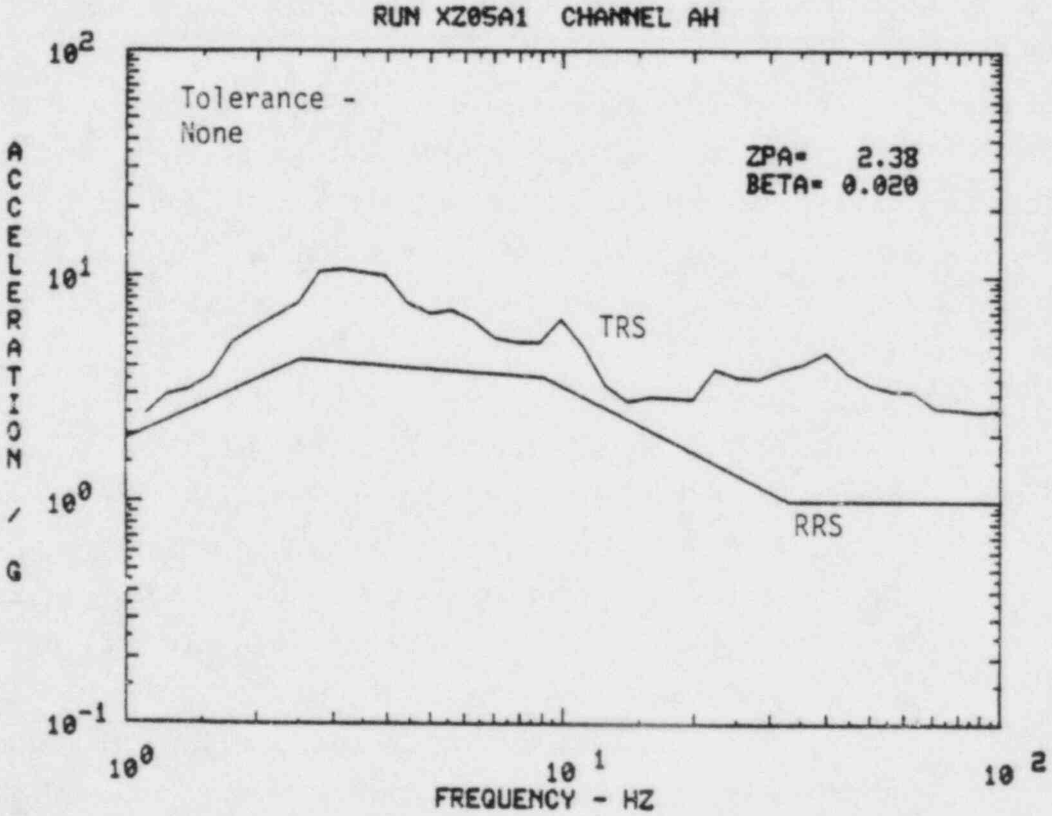
Recommendations

1. Consideration of the proper frequency content for the strong motion portion of synthesized waveforms should be demonstrated and justified. Justification need not be given if correct frequency content is shown by one of the following methods:
    a) Enveloping of the RRS by the TRS within +30% or less at all frequencies, within the amplified region of the RRS. (Note that consideration of the frequency range above the start of the ZPA is handled separately in paragraph 5.4.)


RUN XZ03A1 CHANNEL AH

Tolerance -
1.05 to 1.15 X RRS

Figure 5.1-1 TRS Envelope of RRS for Run 003


RUN XZ05A1 CHANNEL AH

Tolerance -
None

Figure 5.1-2 TRS Envelope of RRS for Run 005

   - b) Show that the shape of the real part of the Fourier Spectrum of the synthesized waveform is frequency compatible with the amplified region of the RRS.
   - c) Show that the shape of the PSD of the synthesized waveform is compatible with the amplified region of the RRS.
   - d) These steps shall be performed with each new synthesized waveform development.

2. Consideration of the proper frequency stationarity for the strong motion portion of the synthesized waveform should be demonstrated and justified. Justification need not be given if correct frequency stationarity is shown by the following methods:
   - a) A time history of the excitation must be recorded and included in the data.
   - b) To demonstrate the validity of the synthesis process, time interval PSD or TRS calculations should be performed and the results shown to be within accceptable limits for one typical case. These calculations need be performed only once and filed to establish the nature of the synthesis process. They need not be performed for subsequent tests that are based on the same procedures.
3. Other waveform characteristics such as coherence and amplitude probability density, or distribution should be considered for those cases where known to be important.
4. In all cases where statistical parameters such as PSD, coherence, etc. are generated, the number of statistical samples and resolution bandwidth used for the calculations should be noted.

5.2 Response Spectrum Envelope Accuracy

Typical current practice allows that in developing test excitation signals, enveloping of the RRS by the TRS can be done so that no more than one point falls below the RRS, and by no more than 10%. Such stringent accuracy on the lower side of a tolerance band is unrealistic, in view of the 1/3 octave resolution bandwidth that is also allowed for a response spectrum calculation. In fact, even at 1/6 octave resolution, if the center frequencies for calculation of the response spectrum are shifted, it is possible that the response spectrum for a given time history can envelope completely for one set of center frequencies, and not for a slightly shifted set of center frequencies.

Recommendations

1. Response spectra calculations for testing purposes should be computed for 1/6 octave or higher resolution.
2. For TRS envelope of the RRS, a point of the TRS may fall below the RRS by 10% or less, provided that the adjacent 1/6 octave points are at least equal to the RRS, and the adjacent 1/3 octave points are at least 10% above the RRS.
3. A maximum of 5 of the 1/6 octave analysis points may be below the RRS, provided that they are least 1 octave apart.
4. Line segments which are used to connect the TRS calculated points are used only for convenience, and are not considered as calculated points of the TRS. Thus, whether they fall above or below the RRS is immaterial.

5.3 Mounting/Shaker Table Interactions

The resonance frequencies of lower bending modes in relatively tall equipment (such as electrical racks and cabinets) has been shown to be very sensitive to mounting and/or inherent shaker table compliance [2]. The usual effect is a reduction of these natural frequencies by as much as 30%, depending on the amount and nature of the compliance present. The amount of biaxial or triaxial shaker compliance can be obtained by performing resonance searches with horizontal excitation along one axis, alternately with the other axes free, and then blocked. Figures 5.3-1 and 5.3-2 show examples of where an electrical rack was tested horizontally on a biaxial table with a free vertical axis. These may be compared with the data in Figure 4.3-4, where the same conditions existed, except that the vertical axis was blocked. The lower bending mode frequency shifted from 23 to 16 Hz because of table compliance in this case. Such an occurrence may or may not influence the test results, depending on the nature of the test excitation. In particular, if significant frequency content is present in the excitation at the

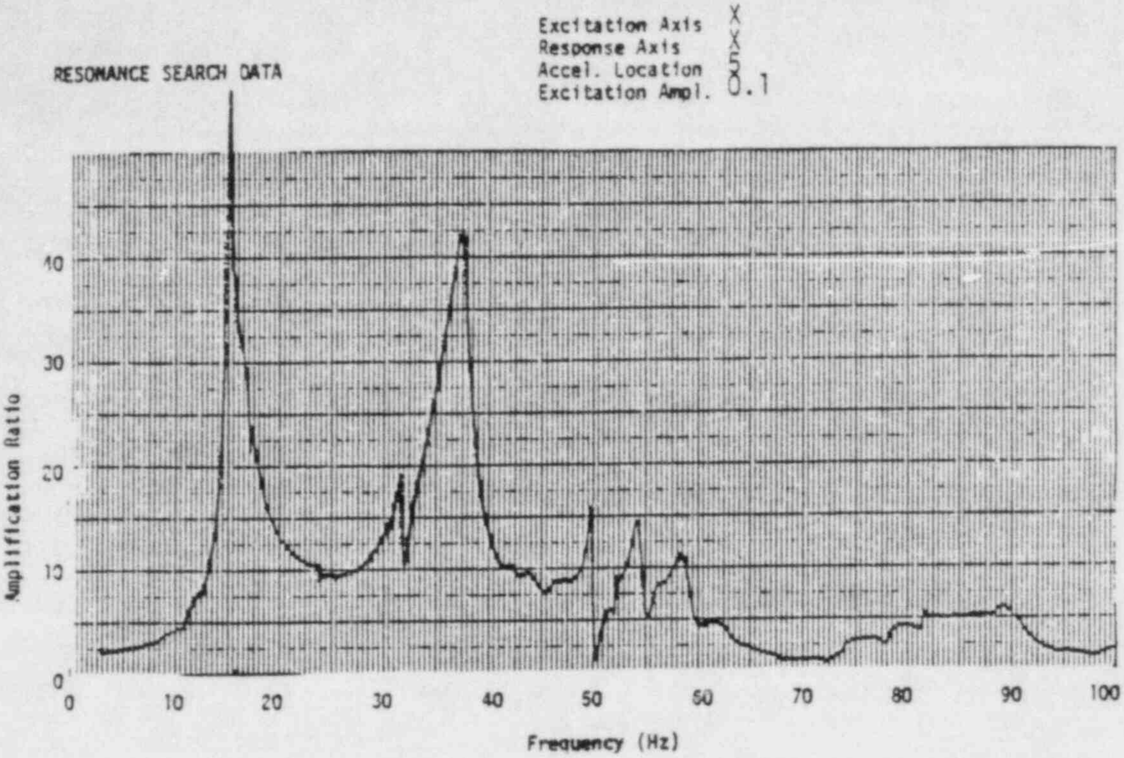


Figure 5.3-1 Position 5 Transfer Function for Sine Sweep with Free Vertical Table

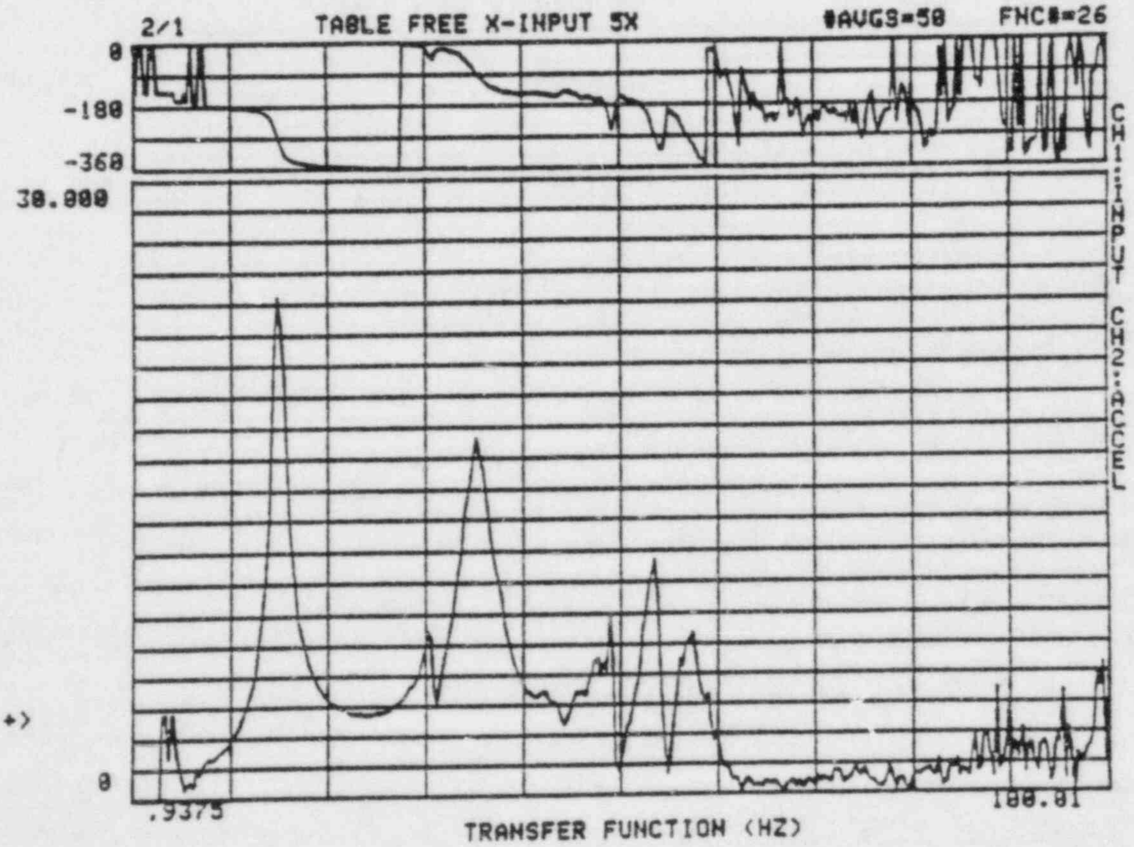


Figure 5.3-2 Position 5 Transfer Function for Random Excitation with Free Vertical Table

true resonance frequency but not at the lower frequency, then an undertest could occur. Furthermore, if the equipment included devices that contained resonances near the true resonance frequency, then an undertest could also occur. At the very least, some consideration of this phenomenon should be included in the test procedure.

Recommendation

Consideration shall be given to potential dynamic interaction between the test specimen and the shaker table, and the approach justified. The following steps are appropriate.

a) If it is obvious that a given specimen will produce a large dynamic overturning moment on the shaker table, or if potential interaction may be expected from experience with similar specimens, the amount of interaction should be established by determining the resonance frequency shifts under free and blocked, off-axis conditions. Performance of a resonance search in a simulated floor-mounted condition is also permissible for this purpose.

b) When interaction is shown to be present, broadening of the response spectrum should be performed in order to account for the frequency shift error.

c) Details of the entire process should be documented in the test report. Justification for the nonuse of this procedure in a specific case should also be recorded.

5.4 Measurement of ZPA

Test excitation waveforms are typically obscured by the presence of an undesirable excessive ZPA that is caused by rattling of loose parts in the table or by nonlinear generation of harmonic frequencies in the table electrohydraulic system [2]. Usually, these extraneous excitations occur at frequencies above the typical cutoff frequency (33 Hz) for seismic simulations. In some cases where ZPA sensitive devices are present, an erroneous malfunction may be generated. However, usually the higher frequency part of the excitation has little effect on the performance of most equipment, and it still functions correctly. Nevertheless, measurement of the desired ZPA for the test (which occurs due to frequency content in the amplified region of the RRS) is rendered difficult because of the presence of the excessive ZPA. Therefore, the amplified region ZPA should be measured and considered in whether the specified ZPA requirements are met.

Recommendation

1. The amplified region ZPA should be used as the basis for meeting ZPA requirements for a test. It can be measured by filtering the excitation signal with a high slope filter (24 dB/octave or greater) above the start of the ZPA on the RRS.
2. This procedure is not to be applied where the rattling of loose parts occurs within the equipment itself. In this case the nonlinear generation of higher frequency content is a genuine part of the test.

5.5 Nonlinearities in Resonance Searches

Some equipment exhibits inherently nonlinear response to excitation, even when mounting and table interaction problems are not present [2]. In such cases, shifting of resonance frequencies and/or increase of damping may occur with increasing excitation amplitude. Nevertheless, the establishment of some set of equivalent linear dynamic properties are necessary for some types of qualification procedures.

Recommendation

When significant equipment nonlinearity is evident from resonance search results, and the use of these data is a requirement in the qualification process, excitation levels of the resonance search should be adjusted so that the response levels are as near as practical to what they will be during the simulated seismic portion (SSE) of the qualification test, without risking fatigue damage. This will assure that damping levels and resonance amplification are approximately appropriate for the SSE excitation levels.

5.6 Nonlinearities in Elevated Responses

Some testing requires the acquisition of response data at elevated locations on equipment, and subsequent use of the data for generating excitation criteria for components to be installed at the elevated locations. Typically, this approach is used in new electrical cabinet or rack designs when the components are not yet available, and is also used in some forms of in-situ testing, where the cabinets or racks cannot be removed from the plant. An example of such a nonlinearity is shown in Figures 5.6-1 and 5.6-2. The PSD's for a Run 003 and 005 horizontal excitation [2] are shown in Figures 5.6-1. At 16 Hz, where a bending mode occurs for the electrical rack from which the data were taken, the excitation PSD's are different by a factor of 4.5 on power (2.1 on amplitude). However, the elevated position 5 data, which appears in Figure 5.6-2, shows an amplitude difference factor of 3.4. Thus, the response ratio increases more than the excitation. Often, the reverse is true. The important point however, is that the two are different due to nonlinearities of some unknown origin. Such behavior is frequently observed in equipment of all types.

Recommendation

When significant equipment nonlinearity is evident from resonance search data, generation of elevated response information should be performed with excitation levels corresponding to the maximum response for the excitation amplitude range considered, without risking fatigue damage.

5.7 Line Mounted Equipment

Current test specifications for line mounted equipment are primarily based on IEEE Standard 382. It is understood that in service the equipment will be excited dominantly at the resonance frequencies of the piping system on which it is to be installed. However, the exact frequencies at which the resonances will occur are usually unknown. Furthermore, it is desirable to perform a more generic test, rather than have the equipment qualified to only one specific installation. Therefore, the usual test involves the application of a series of sine beats, with each beat sequence centered at 1/3 octave frequencies from 1 to 33 Hz. The sine beat waveform is intended to simulate a single dominant mode resonant response to random ground level excitation, and the beat amplitude is selected as the maximum response amplitude expected on the pipe location.

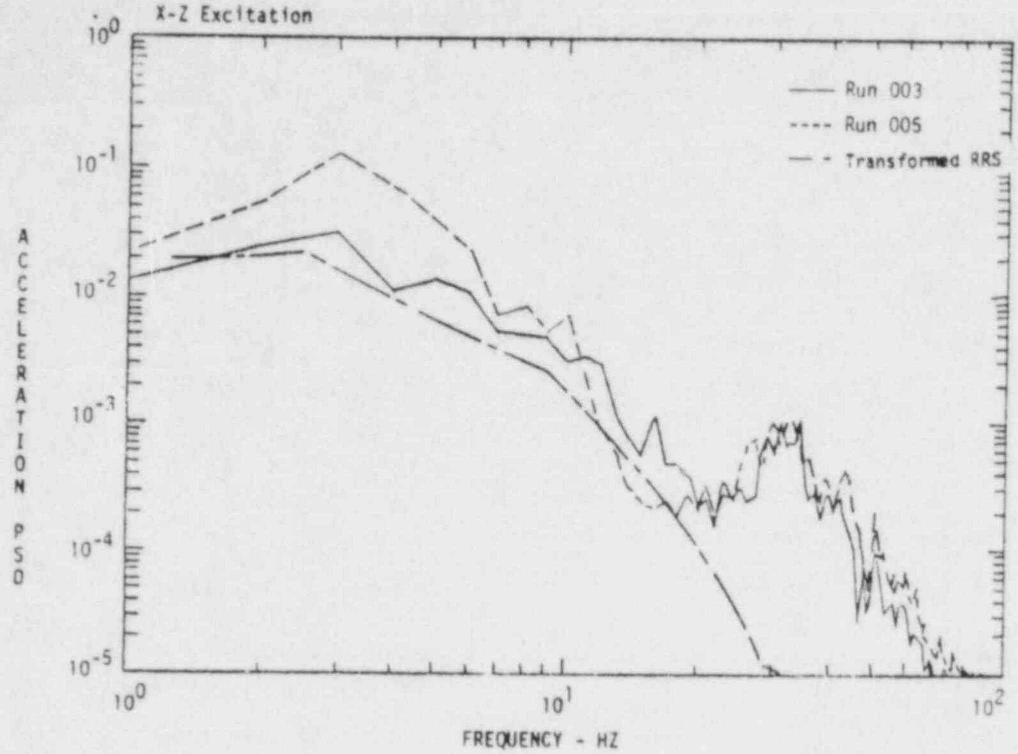


Figure 5.6-1 Comparison of PSD's for Horizontal Excitation with Different Runs

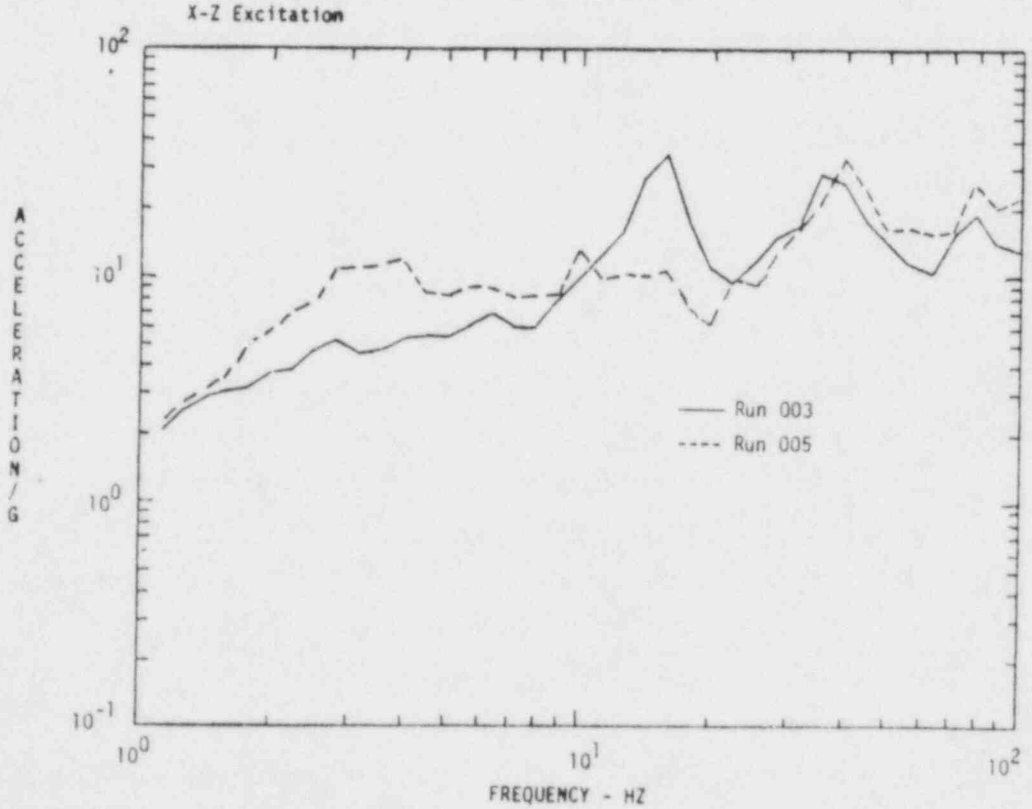


Figure 5.6-2 Comparison of Response Spectrum at Position 5 for Different Runs

The above test is appropriate conceptually, however recent research [11] has produced an alternate test approach, which is less severe than that specified above but still conservative. It is well known that a ground level type random excitation produces a narrow band random response at the resonance frequencies of structures. The narrow band random response is similar to a sine wave at the structural resonance frequency, but its amplitude fluctuates in a random manner. Figure 5.7-2 shows such a response time history to the earthquake waveform shown in Figure 5.7-1. There are two important aspects of this type of motion compared to discrete sine beats. First, a narrow band random test waveform can be generated just as readily in the laboratory, and it can be swept slowly throughout the frequency range, so that no frequency spaces are left between 1/3 octave points. Second, the peak amplitude distribution of the narrowband random waveform is different, and generally produces less severe tests than does the sine beat. Figure 5.7-3 shows that the peak amplitude density for a resonant system response to an earthquake ground motion should be nearly a Rayleigh distribution. Figure 5.7-4 shows that the same system response to a narrow band random excitation is also Rayleigh, and that the response distribution to a sine beat is significantly different. Results from that study [3] also indicate that the RMS level for a narrow band random can be set at 70% of the RMS for a sine beat, and produce the same peak levels of response.

Recommendation

In addition to the present discrete sine beat test specified by IEEE Standard 382 for line mounted equipment, an alternate swept narrow band random test should be allowed. The bandwidth should be no greater than 2 Hz, and the RMS level should be set at 70% of that specified for sine beat tests. (From Figure 5.7-4 it can be seen that the peak/RMS ratio for a typical sine beat waveform with 1 beat pause is 2.6.) The total test time should be set equal to the aggregate of the total individual 1/3-octave sine beat dwells that are prescribed in IEEE 382. The sweep rate should be set so that one sweep up in frequency results. Actuation of the equipment for functional purposes should be performed to coincide with any observed resonance conditions, as indicated by an initial resonance search. Furthermore, if the most conservative

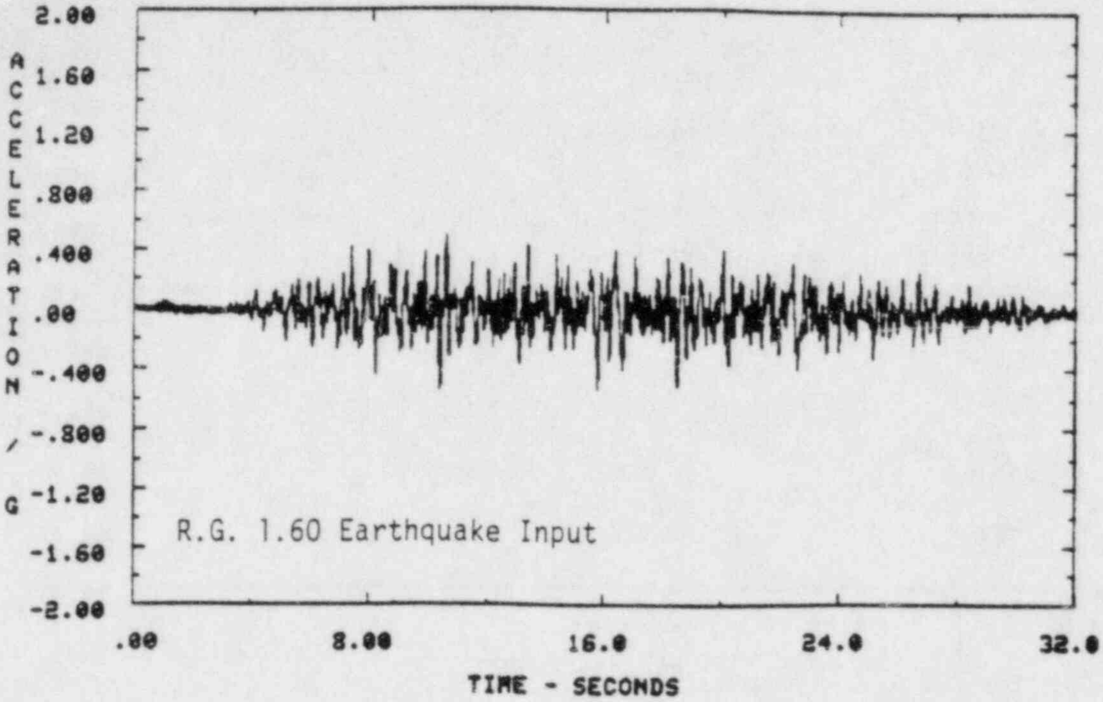


Figure 5.7-1 Excitation Waveform for Simulated Earthquake

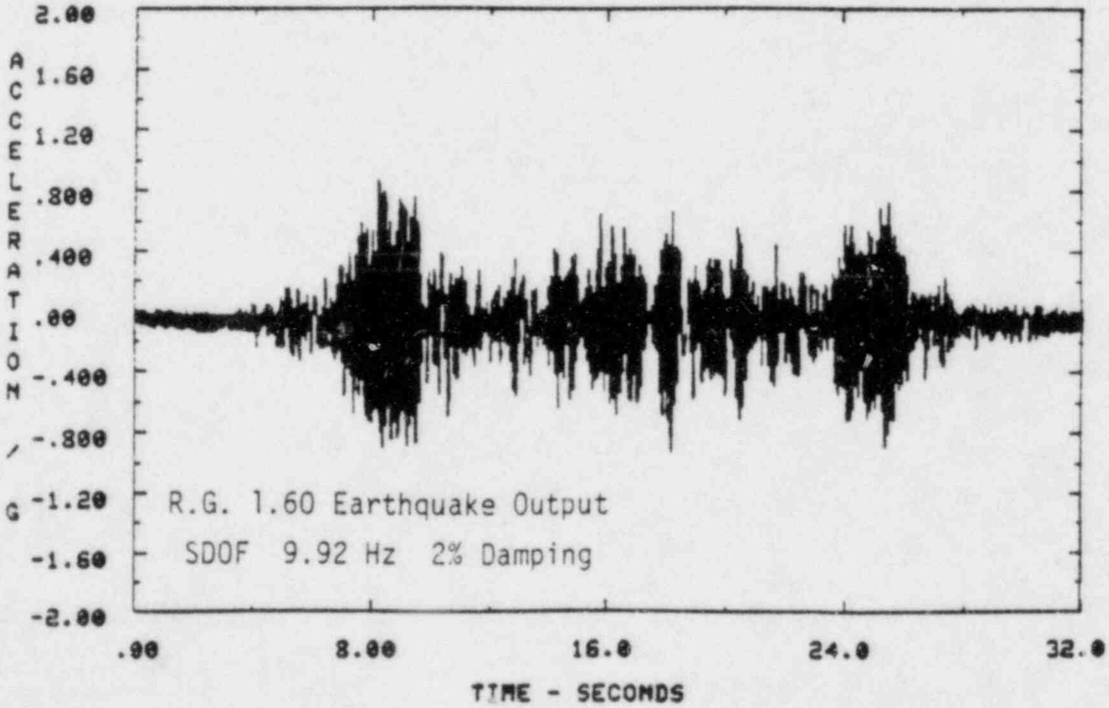


Figure 5.7-2 Oscillator Response Waveform for Simulated Earthquake

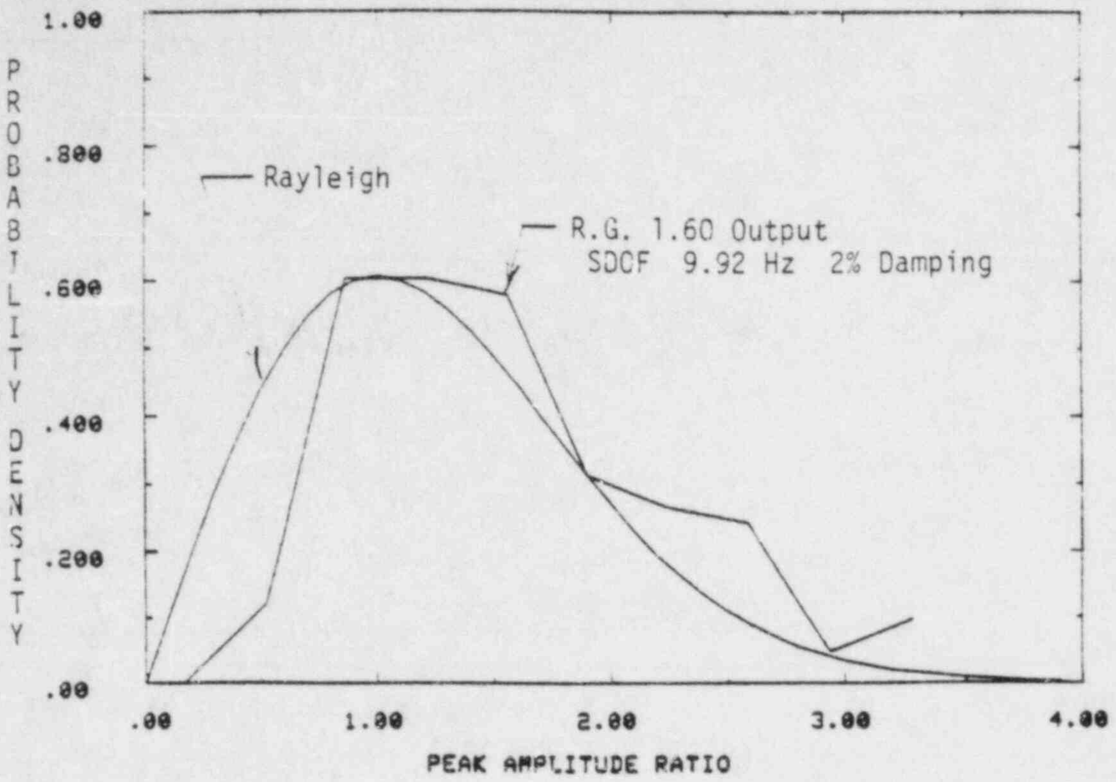


Figure 5.7-3 Peak Probability Density for Simulated Earthquake Response

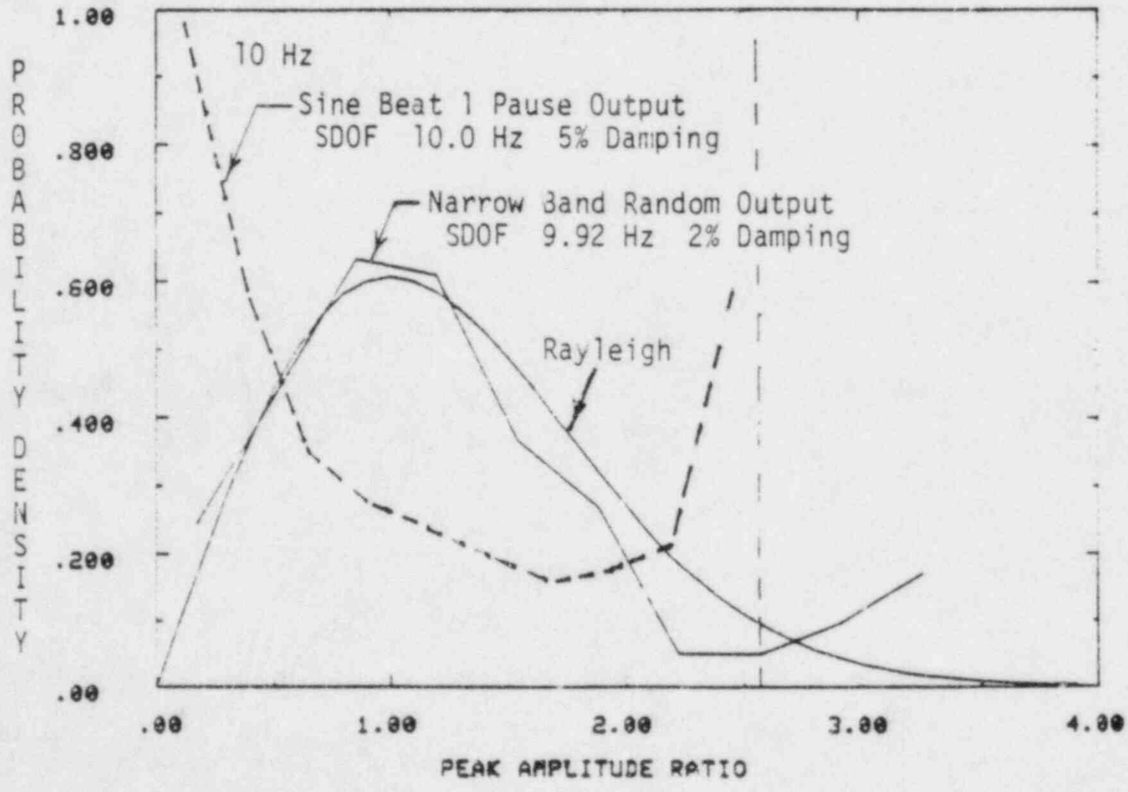


Figure 5.7-4 Peak Probability Density for Various Waveform Responses

conditions are desired, multiple functional operations can be made to coincide with times for large excitation bursts for the narrow band random motion (e.g., see Figure 5.7-2).

5.8 Resonance Search With Random Excitation

Use of modal analysis equipment along with random or transient excitation is rapidly increasing in popularity as a method for resonance search. With appropriate laboratory equipment the hard copy output is in the form of magnitude and phase (or real and imaginary) components of transfer functions. Use of these methods is desirable for many cases, particularly for use with laboratory computers where much data can rapidly be generated. In this manner the methodology is superior to steady state sinewave methods. However, correct implementation of the methods requires considerable sophistication and can easily lead to error for the unwary.

Recommendation

Resonance searches conducted with random or transient excitation should be performed with special care. In particular, all data and computations include statistical philosphy, and therefore the number of statistical samples in developing such information should be noted. Likewise, the resolution bandwidth should be such that about four bandwidths are present for the narrowest resonance peak to be resolved. Hence the data should be computed with statistical parameters that are commensurate with the accuracy desired.

6.0 RECOMMENDED FURTHER STUDIES

In Task 1 of the current program an initial survey [1] showed that a variety of technical issues/anomalies existed in the equipment seismic qualification process. Many of these items have been evaluated in the program and the results of this evaluation have been reported in References [1] and [2]. Nevertheless, some of the issues remain uncertain at this point, either because they were considered of lower priority at the start of the program and subsequently became more important, or because the issue was not sufficiently defined at the start of the program. In either case the result at this point is that more investigation must be recommended before the issue can be brought into the categories already described heretofore in this document. Therefore, this section consists of an identification of such additional issues, and recommendations on what efforts are yet needed for their resolution. Relative priorities will be indicated for each item as 1 to 3, from highest to lowest priority, although all three categories are very important on an absolute basis. Justification of the priority is also given.

6.1 Extension of Response/Power Spectrum Transformation

In Section 4.1 we described the current state of response/power spectrum transformations, and recommended their use in several practical problem areas frequently encountered in seismic qualification of equipment. Use of this methodology to date has been principally restricted to seismic excitation, and includes waveforms with peak/RMS ratios characteristic of the strong motion portion of earthquakes. Various other types of waveforms are typically employed in qualification by test, and furthermore, other types of waveforms are experienced by operational loading of equipment. Therefore, effective application of this methodology to other practical areas of qualification is highly probable.

Recommendation

Response/power spectrum transformation methodology should be studied in more detail to consolidate its use for earthquake response prediction problems, and to determine its potential for use in response prediction to other types of loading. Two immediate parameters that enter the transformation should be explored--the time duration of the assumed stationary motion and the peak/RMS ratio, which inherently is related to the instantaneous amplitude probability density (or amplitude distribution). An understanding of their influence on the transformation is essential to potential application to nonearthquake type waveforms. At the same time, an even better understanding of its limits for use in earthquake problems will also result. This issue is of Priority 1, since its benefits are of immediate use in many existing practical problems.

6.2 Cross Coupling Effects

The potential effects of cross coupling in equipment and its potential influence on the qualification process were recognized at the start of this program. However, it was originally placed at a lower priority, since it was assumed that current independent biaxial test methodology was conservative. However, during the last three years some factors have developed which have increased the emphasis on this problem area. Several independent axis triaxial shakers have been built during this period, and the natural question now emerges, "to what extent are these systems superior to less than triaxial systems, if indeed they are, when all factors are considered?" Furthermore, results of the present programs have shown that the issue enters the qualification process in more ways than one, and in fact sufficient data is currently not being acquired to implement the capability of a triaxial shaker for all practical situations.

Figures 6.2-1 and 6.2-2 show where some difference in response occur at an elevated location on equipment when simulated triaxial, rather than biaxial testing is used. This difference occurs, of course, principally in the frequency vicinity of structural modes which experience cross-axis coupling. It is the first problem area which affects qualification, in that the correction methodology for less-than-triaxial excitation is uncertain. The second problem area results from the fact that building response to ground motion is also often coupled. As a result, floor motions (which form the excitation to equipment) are also coupled, and cross-axis motions become highly coherent, rather than

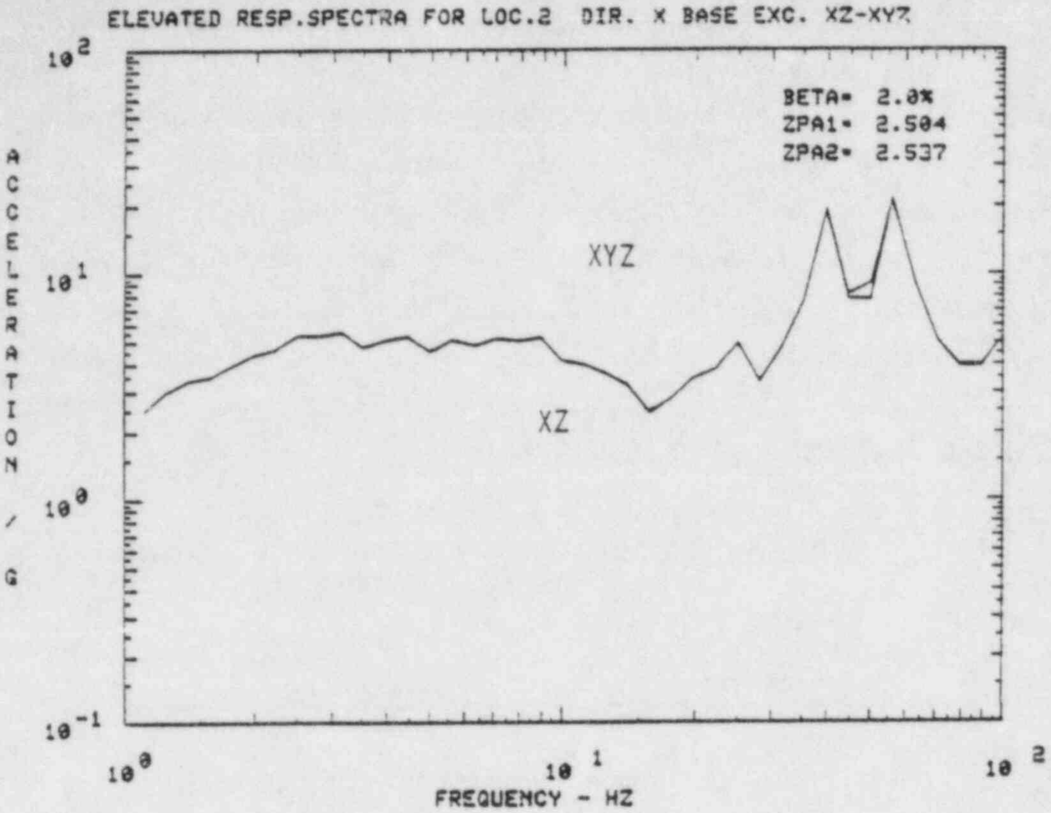


Figure 6.2-1 Response at Location 2 in X-Direction for XZ and XYZ Excitation

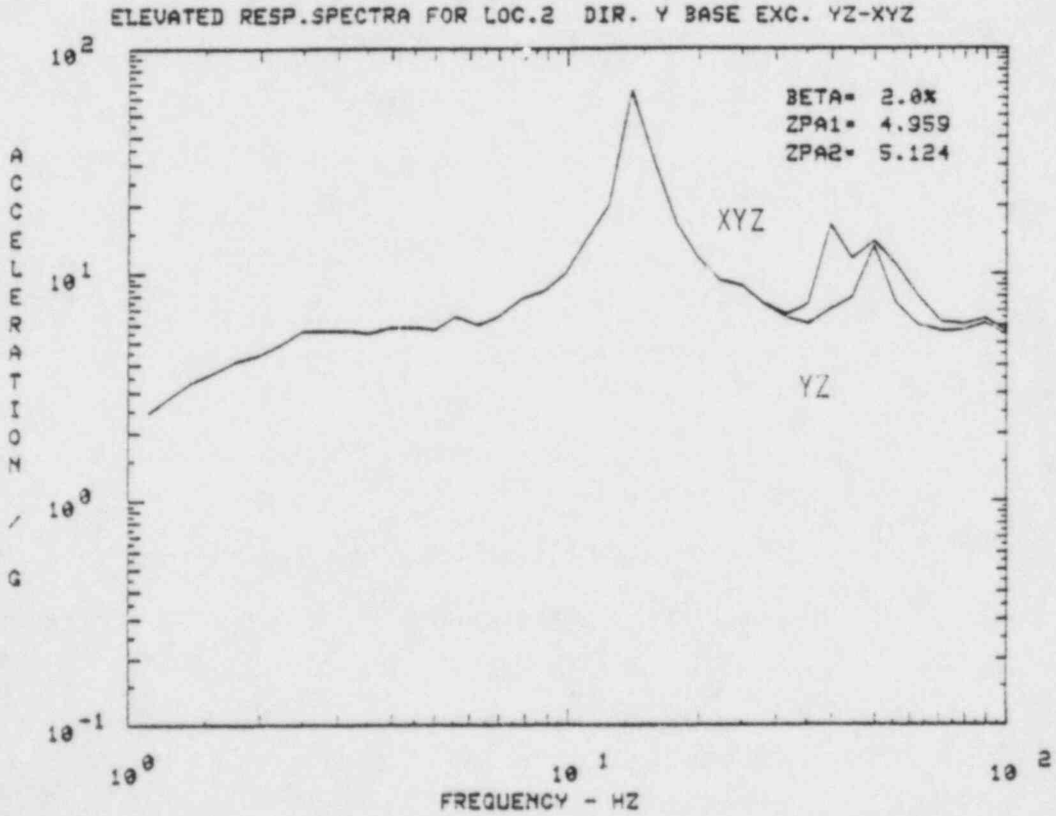


Figure 6.2-2 Response at Location 2 in Y-Direction for YZ and XYZ Excitation

incoherent as ground motion is recognized to be. None of the present guidelines address either of these problem areas.

A summary of the state-of-the-art is shown in Table 6.1. An important point to recognize is that dynamic cross coupling per se, is not necessarily important to simulate in a test. It becomes important only if the motion influences the fragility of the equipment. In any case, unfortunately no recognized methodology has been defined for handling either aspect of the problem.

TABLE 6.1 STATE-OF-THE-ART FOR CROSS COUPLING IN SEISMIC TESTING

1. Equipment cross coupling is significant only if it influences the fragility level
   - EFCC - equipment fragility cross coupling
2. Ground level tests without EFCC
   - Multiaxis or uniaxis tests with RRS sufficient
3. Ground level tests with EFCC
   - Independent triaxial shaker with equipment RRS provides most direct test
   - Biaxial or uniaxial shakers adequate with corrected equipment RRS
   - Nature of equipment RRS correction remains unspecified
   - Estimate of error without equipment RRS correction remains uncertain
4. Building cross coupling is significant only if it influences the equipment fragility level
   - No present methodology includes this effect
   - Multiaxis test with coherence dependent on frequency is indicated
   - Estimate of error in present methodology remains uncertain

Recommendation

Further investigation of the cross coupling problem should be conducted. It would be most efficient to include the use of the electrical rack, which has already been studied in Task 1 of this program. A finite element model of the rack is already available, and in fact preliminary analytical studies have already been conducted and resulted in data of the type given in Figures 6.2-1 and 6.2-2. It would be most informative to alter the characteristics of the rack by adding additional off-center masses, so that coupled modes were lowered even further into the earthquake range. The analytical model should be modified to include these effects. Then, experiments on the actual specimen should be conducted for both biaxial and triaxial excitation. The results should be used to develop the differences expected under each type of excitation, and correction factors applied to assure conservatism in all cases. Furthermore, the potential effects of specimen/shaker table coupling due to table compliance should be explored in all cases. Also, the consequences of ignoring the high coherence of coupled floor motions should also be included. If it turns out to be important, then methodology for its inclusion in qualification tests should be developed. This issue is considered Priority 2. This means it can be started somewhat later than the Priority 1 tasks, but it is imperative that it be accomplished in any long term extended program.

6.3 Fragility

The concept of fragility has been recognized to be potentially important to equipment qualification by most engineers, yet it has been put to only cursory use to date. The most probable reason is the lack of any standardized approach to definition, acquisition, compilation, and disemination of fragility data. That is, development of fragility methodology is still essentially in its infancy compared to proof test methodology.

A general definition of fragility borrowed from aerospace developments has been discussed in Reference [3]. In this case the concept was used as an essential ingredient for comparison of test severities. In the most general sense, fragility is recognized as a surface in three-dimensional parametric space, as shown in Figure 6.3-1.

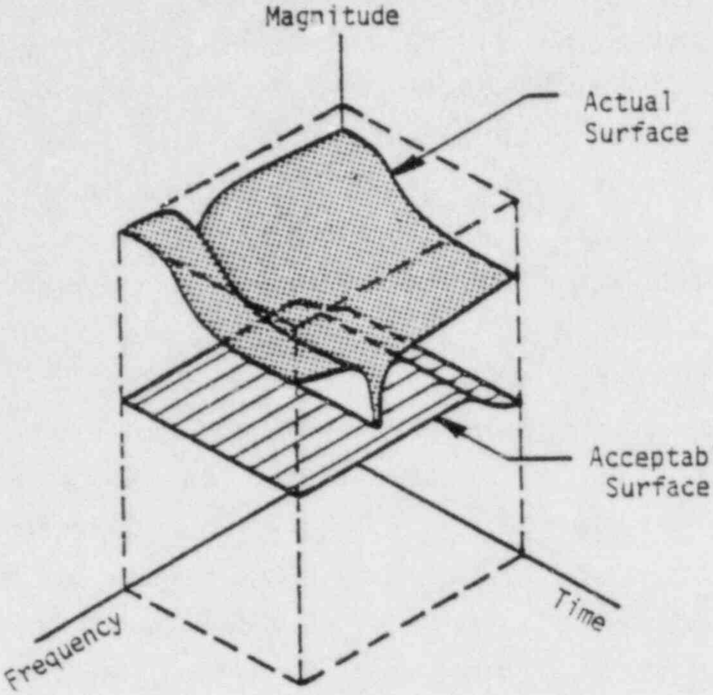


Figure 6.3-1 Comparison of Actual with Acceptable Fragility Surface

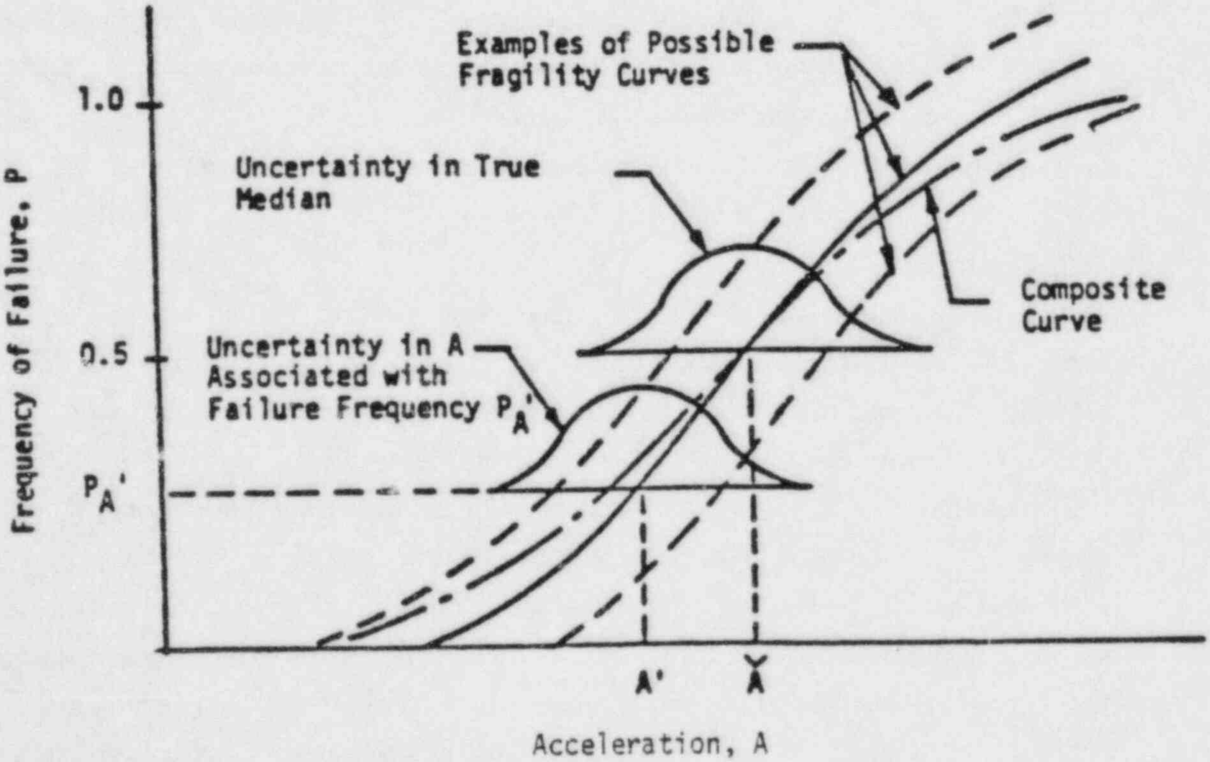


Figure 6.3-2 Simplified Representation of Fragility Curve

The coordinates for the space are magnitude, frequency, and time. For most equipment of concern in nuclear plants, time is not of such importance for seismic environments, and the surface reduces to a fragility function in the magnitude/frequency plane. Nevertheless, fragility also is a statistical distribution as a function of amplitude, as shown in Figure 6.3-2. The latter description of fragility has been emphasized for use in risk analysis of plants [12]. However, the connection between the descriptions in the above two figures has not yet been completely established. In particular, use of a single parameter description such as acceleration amplitude, presumes that frequency distribution is similar in all cases, or that it is unimportant for that piece of equipment.

Generally, fragility has been considered in terms of seismic or dynamic qualification. However, it can similarly be considered appropriate for other environments as well. For example, fragility could be measured by temperature as magnitude, and time, where frequency would not not be appropriate. Thus, the magnitude parameter could more generally be labeled as the stress, or challenge factor of a given environment. In this general sense, fragility could become a very useful design tool, by which margins of operations are automatically established. However, significant research remains to be conducted before this could be accomplished. Task 4 of the present program allows an initial attempt at this approach. However, the overall problem is much too large for the resources available, and extended work will be necessary.

Recommendation

A general program of research on the potential use of fragility in equipment qualification should be pursued. This program should include several approaches.

1. A review of the various aspects of equipment qualification where fragility is most urgently needed. Potential use of some existing qualification proof test data for fragility purposes should be investigated. (Some of this will already be accomplished under Task 4 of the present program.)

2. Development of a standardized set of parameters for measure of fragility that is applicable to all practical uses. For example, acceleration response spectral amplitude for ground level frequency content may be appropriate for seismic qualification.
3. Compilation of a best known set of standardized fragility data for the generic equipment list previously shown in Table 2.1. An initial attempt at this task has been reported in Reference [13]. However, this approach includes data acquired under a variety of methodology that must be standardized to ground level data.
4. Development of methodology for conversion to standardized ground level data for fragility data that may have been acquired by other methodology.
5. Conduct of an experimental program for verification of fragility measured on a selected set of equipment specimens.
6. Development of methodology for transfer of standardized fragility data to specific floor level locations, to allow prediction of fragility under all practical uses. The methodology should include format for input to seismic risk analysis.
7. Recommendations for change of qualification guidelines should be made to include more general use of the standardized fragility data and methodology developed.

This task is considered Priority 1 because of its relationship to test correlations, and for application in risk analyses. It will require a more fundamental and long term effort, since the state of development and use of the fragility concept lags all other areas discussed in this report.

6.4 In-Situ Testing/Analysis

As applied to equipment qualification in-situ methodology consists of two basic parts: (1) acquisition of experimental data and development of base-fixed analytical models therefrom, and (2) transformation to moving axes models and prediction of subsequent seismic response. The essentially new aspects of this methodology developed under the present program have been previously described in Section 4.4. In its present form, the developed approach is the first known publication in the open literature, and is already useful for solving typical in-situ qualification problems. However, as with any new methodology, there are several very desirable improvements which have become apparent to us in the short time of the methodology application. These stem first from the relative computational inefficiency of the UMASS program for highly underdetermined (few modes with many nodal measurements) systems. Likewise, there was no automated procedure available for checking the quality of measured data of modal vectors. Finally, the method has been applied so far to only a few check cases where accurate independently developed analytical models are available for verification. Thus, several areas exist where the developed in-situ test/analysis can be significantly improved by some extended effort.

Recommendations

1. An improved numerical algorithm should be developed to improve the reliability and reduce the computational effort in the current digital program. This can be accomplished by including the mass smoothing effects into the optimization approach by merging the present MASOPT and UMASS programs. Specifically one can form the functional

$$F(m_i) = (\tilde{m}_{11}-1)^2 + \sum_{p=1}^{R} \sum_{q=p+1}^{R} (\tilde{m}_{pq})^2 + \gamma\sigma^2(m_i)$$

   where γ is a parameter that is a measure of the smoothness of the mass distribution, $\gamma = [0.0, 0.2]$. The mass parameters in this equation are identified in References [2,5].

2. Develop an algorithm for checking the quality of the measured data in order to weed out poorly defined mode shapes of higher order. Such modes are known to degrade the results rather than improve them.

3. Apply the improved methodology to several typical examples of equipment where companion analytical models are also developed by an independent approach. Compare results from both models to verify the accuracy of the in-situ approach for equipment having a wide range of physical characteristics.
4. Acquire other existing in-situ test/analysis methodology and compare predictions to above results.

This task should be considered Priority 2. It can also be started somewhat later, but is essential to the total program.

6.5 Test Correlation Correction Factor Limits

Establishment of a lower limit for the test correlation interaction correction factor α_1 is highly desirable. Such a lower limit would preclude the requirement for establishing transfer function data for a given specimen. Furthermore, a sound basis is also lacking for justifying the cross correlation correction factor $\alpha_2 = 1/1.2$. This value has merely been proposed as a best guess from experience.

Recommendations

1. Conduct an analytical investigation to establish a lower limit for the test correlation correction factors α_1 and α_2. Outline details for use of these fators in comparing various single frequency and multiple frequency test criteria. This task is Priority 1 as it is of immediate use in resolving the Task A46 Unresolved Safety Issue.

6.6 Aging and Synergistic Effects

The effort of this program has been concentrated in the area of seismic qualification of equipment for nuclear power plants. However, it has also been recognized that aging can play a role in the fragility level, and therefore the qualification of specific equipment. An extensive NRC program at Sandia National Laboratories is in progress to determine the influence of aging and synergistic (combined radiation and thermal aging) effects on the performance of equipment. At present there is no consensus as to the level to which aging can degrade the functionality of all types of equipment. The resulting influence on the seismic qualification is not known.

Aging may also play a role in the determination of vibration fragility levels. It must be recognized that most existing fragility data has been obtained on unaged equipment. On the other hand, qualification of equipment has been performed on both aged and unaged equipment. To establish the consistent data base of fragility information described previously, it will be necessary to determine some quantitative correction factor to account for aging.

Recommendations

1. Results of the NRC program at Sandia Laboratories should be summarized and the influence of aging on seismic qualification specifically addressed.
2. Fragility data should be standardized so that they represent the functionality of equipment in an aged state.
3. Aging and synergistic effects should be categorized according to the equipment list given in Table 2.1

Present information indicates that the influence of aging on seismic qualification may not be as significant as other parameters described above. Furthermore, other ongoing programs are currently addressing this problem. Therefore, this task is considered Priority 3 within the context of this program.

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13. ABSTRACT (200 words or less)

The Research Program for Seismic Qualification of Nuclear Plant Electrical and Mechanical Equipment has spanned a period of three years and resulted in seven technical summary reports, each of which covered in detail the findings of different tasks and subtasks, and have been combined into five NUREG/CR volumes.

Volume 3 presents recommendations for improvement of equipment qualification methodology and criteria. These recommendations are grouped into categories: standardization of procedures, demonstration of adequate methodology, a new methodology and procedural clarification/modification. The fifth category identifies issues where adequate information does not exist to allow a recommendation to be made.

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