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COMBINING MODAL RESPONSES AND SPATIAL COMPONENTS IN SEISMIC RESPONSE ANALYSIS

A. INTRODUCTION

This revised regulatory guide provides licensees and applicants with improved guidance concerning methods that the staff of the U.S. Nuclear Regulatory Commission (NRC) considers acceptable for combining modal responses and spatial components in seismic response analysis of nuclear power plant structures, systems, and components (SSCs) that are important to safety.

Appendix A, "General Design Criteria for Nuclear Power Plants," to Title 10, Part 50, "Domestic Licensing of Production and Utilization Facilities," to the *Code of Federal Regulations* (10 CFR Part 50), Criterion 2, "Design Bases for Protection Against Natural Phenomena," requires, in part, that nuclear power plant SSCs important to safety must be designed to withstand the effects of natural phenomena (such as earthquakes) without loss of capability to perform their safety functions. Such SSCs must also be designed to accommodate the effects of, and be compatible with, the environmental conditions associated with normal operation and postulated accidents. Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants," to 10 CFR Part 50 specifies, in part, requirements for implementing General Design Criterion 2 with respect to earthquakes.[1]

[1] Appendix S to 10 CFR Part 50 applies to applicants for a design certification or combined license pursuant to 10 CFR Part 52, "Early Site Permits; Standard Design Certifications; and Combined Licenses for Nuclear Power Plants," or a construction permit or operating license pursuant to 10 CFR Part 50 after January 10, 1997. However, the earthquake engineering criteria in Section VI of Appendix A to 10 CFR Part 100 continue to apply for either an operating license applicant or an operating license holder whose construction permit was issued before January 10, 1997.

The U.S. Nuclear Regulatory Commission (NRC) issues regulatory guides to describe and make available to the public methods that the NRC staff considers acceptable for use in implementing specific parts of the agency's regulations, techniques that the staff uses in evaluating specific problems or postulated accidents, and data that the staff need in reviewing applications for permits and licenses. Regulatory guides are not substitutes for regulations, and compliance with them is not required. Methods and solutions that differ from those set forth in regulatory guides will be deemed acceptable if they provide a basis for the findings required for the issuance or continuance of a permit or license by the Commission.

This guide was issued after consideration of comments received from the public. The NRC staff encourages and welcomes comments and suggestions in connection with improvements to published regulatory guides, as well as items for inclusion in regulatory guides that are currently being developed. The NRC staff will revise existing guides, as appropriate, to accommodate comments and to reflect new information or experience. Written comments may be submitted to the Rules and Directives Branch, Office of Administration, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001.

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This guide describes methods that the NRC staff considers acceptable for complying with the agency's regulations regarding the following aspects of seismic response analysis:

(1) combining the responses of individual modes (in the case of the response spectrum method) to a component of the three orthogonal spatial components of earthquake motion (two horizontal and one vertical), to find the representative maximum response of interest (such as displacement, acceleration, shear, moment, stress, or strain) for a given element of a nuclear power plant SSC

(2) combining the maximum responses (in the case of the time history method) or the representative maximum responses (in the case of the response spectrum method) of an SSC, when such responses are calculated either separately (for the response spectrum method or the time history method) or simultaneously (for the time history method) for each of the three orthogonal spatial components (two horizontal and one vertical) of an earthquake

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This regulatory guide contains information collections that are covered by the requirements of 10 CFR Part 50, which the Office of Management and Budget (OMB) approved under OMB control number 3150-0011. The NRC may neither conduct nor sponsor, and a person is not required to respond to, an information collection request or requirement unless the requesting document displays a currently valid OMB control number.

B. DISCUSSION

Background

For several decades, the nuclear industry has used the response spectrum method and the time history method (described below) for the seismic analysis and design of nuclear power plant structures, systems, and components (SSCs) that are important to safety. In 1976, the NRC issued Revision 1 of this guide, which described then up-to-date guidance for using the response spectrum and time history methods for estimating SSC seismic response. Since that time, research in the United States has resulted in improved methods for combining modal responses and spatial components that provide more accurate estimates of SSC seismic response, while reducing unnecessary conservatism. This guide (Revision 2) describes methods that the NRC staff considers acceptable in view of those improvements. The more conservative methods of combining modal responses (as described in Revision 1) remain acceptable. However, if applicants for new licenses choose to use Revision 1 methods for combining modal responses, their analyses should address the residual rigid response of the missing mass modes (as discussed in Regulatory Positions C.1.4.1 and C.1.5.1 of this guide). Licensees of existing operating plants are also encouraged to consider the residual rigid response of the missing mass modes in their seismic analyses of SSCs (as discussed in Regulatory Positions C.1.4.1 and C.1.5.1) when they choose to use Revision 1 methods for combining modal responses, because doing so will produce more accurate results.

It is noted that systems or components (e.g., piping) may be supported at several locations either within a single structure or in two separate structures (multi-supported systems or components), and the motions of the primary structure(s) at each support location may be quite different. An acceptable approach for analyzing systems or components supported at multiple locations within a single structure is to define a uniform response spectrum (URS) that envelops all of the individual response spectra at the various support locations. The URS is applied at all support locations to calculate the maximum inertial responses of the system or component. This is referred to as the uniform support motion (USM) method. The modal and spatial combination methods described in this regulatory guide apply only when using the USM method for response spectrum analysis of multi-supported systems or components (such as piping).

In addition, the relative displacements at the support points should be considered. Conventional static analysis procedures are acceptable for this purpose. The maximum support displacements are imposed on the supported item in the most unfavorable combination. The responses attributable to the inertia effect and relative displacements are then combined using the absolute sum method.

The USM method can result in considerable overestimation of seismic responses. In the case of multiple supports located in a single structure, an alternative method is to use the independent support motion (ISM) approach. See Section 2 of Reference 1 for the current NRC position on use of the ISM method. Any future changes to the NRC position will be addressed in future revisions to NUREG-0800, Standard Review Plan (SRP), Section 3.7.3 (Ref. 2).

In lieu of the response spectrum approach, time histories of support motions may be used as excitations to the system or component. Because of the increased analytical effort compared to the response spectrum techniques, usually only a major equipment system would warrant a time history approach. However, compared to the response spectrum envelope method for multi-supported systems or components, the time history approach provides more realistic results in some cases.

Combination of Individual Modal Responses

For the purpose of seismic design of a nuclear power plant structure, system, or component (SSC), the representative maximum response of interest for design (e.g., displacement, acceleration, shear, moment, stress, strain) can be obtained by combining the corresponding maximum individual modal responses derived from the response spectrum method (e.g., see References 3 or 4). In general, it is unlikely that the maximum individual modal responses would all occur at the same time during an earthquake. Thus, it is necessary to identify appropriate combination methods to obtain the representative maximum response of interest from the maximum individual modal responses.

All methods utilized to combine seismic responses of individual modes obtained from the response spectrum method can provide only approximate representative maximum values, which are not exact in the sense of a time history method. The goal is to develop methods that enable one to estimate the maximum responses of interest as accurately as possible for the design of nuclear SSCs. The time history method, applying either modal superposition or direct integration, has been used by researchers as a benchmark for gauging the degree of accuracy of these combination methods.

Since the issuance of Revision 1 of Regulatory Guide 1.92 in 1976, research in the United States has resulted in improved methods for combining modal responses that provide more accurate estimates of SSC seismic response, while reducing unnecessary conservatism. NUREG/CR-6645, "Reevaluation of Regulatory Guidance on Modal Response Combination Methods for Seismic Response Spectrum Analysis" (Ref. 5), documents the results of an NRC evaluation of these recent developments for modal response combination, which includes a literature review and extensive analytical efforts, and provides the technical bases for the regulatory positions on combination of individual modal responses delineated in Section C.1 of this current guide (Revision 2).

For the purpose of discussion, the broad-banded spectrum in Figure 1 is chosen. However, this guide and the following discussion are applicable to all types of response spectra. This includes broad-banded spectra, such as a design ground spectrum, as well as single-peaked, narrow-banded spectra (Figure 2) and multiple-peaked, narrow-banded spectra (Figure 3), typical of in-structure spectra. Regulatory Position C.1.3 of this guide defines $f1$, $f2$, and f_{zpa} as used in Figures 1, 2, and 3.

The seismic response of interest with regard to an SSC consists of two parts, which are referred to (in structural dynamics) as the damped-periodic (or simply "periodic") response and the "rigid" response. (In the theory of vibrations, these two parts are referred to as "transient" and "steady-state," respectively.) These two parts of the seismic response correspond respectively to the homogeneous and particular solutions of the differential equation of motion of an SSC. The periodic responses have the frequencies of the oscillators (or individual modes), and the rigid responses have the frequencies of the input motion. For a more detailed discussion of periodic and rigid responses, see Chapter 3 of Reference 6.

For periodic modal responses with sufficiently separated frequencies, as indicated in Revision 1 of this guide, Goodman, Rosenblueth, and Newmark (Ref. 7) showed that the Square-Root-of-the-Sum-of-the-Squares (SRSS) method is the appropriate method to combine these modal responses. When modes with closely spaced frequencies are present, several conservative methods presented in Revision 1 of this guide can be used to combine these modal responses. Research since the 1970s (e.g., Refs. 8 and 9) has shown that for periodic modal responses, the double sum equation with appropriate formulas for calculating modal correlation coefficients will more accurately combine modal responses for modes with closely spaced frequencies. For modes with sufficiently separated frequencies, this double sum equation reduces to the SRSS method.

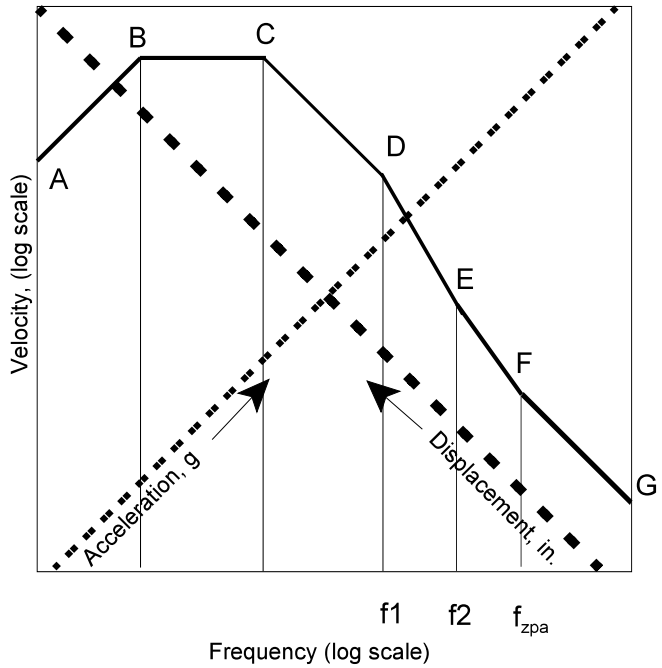

Figure 1. Regions of a broad-banded response spectrum

KEY REGIONS IN FIGURE 1

AB - amplified periodic spectral displacement
BC - amplified periodic spectral velocity
CD - amplified periodic spectral acceleration
DE - transition from amplified periodic spectral acceleration to rigid spectral acceleration
EF - transition from rigid spectral acceleration to maximum base acceleration
FG - maximum base acceleration

When using the response spectrum method, in most cases, it is not practical to calculate all mode shapes and frequencies. Research since the 1980s has shown that in the regions of rigid modal responses, the appropriate method to combine rigid responses is the algebraic sum method (Ref. 10). Some nuclear power plant SSCs may have a number of important modes beyond the zero period acceleration (ZPA) frequency (f_{zpa}). As discussed in Regulatory Position C.1.4, the residual rigid response of the missing mass modes should be addressed (Refs. 11 and 12); otherwise, it may result in underestimation of some SSC element forces and moments in the vicinity of supports, as well as underestimation of some support forces and moments.

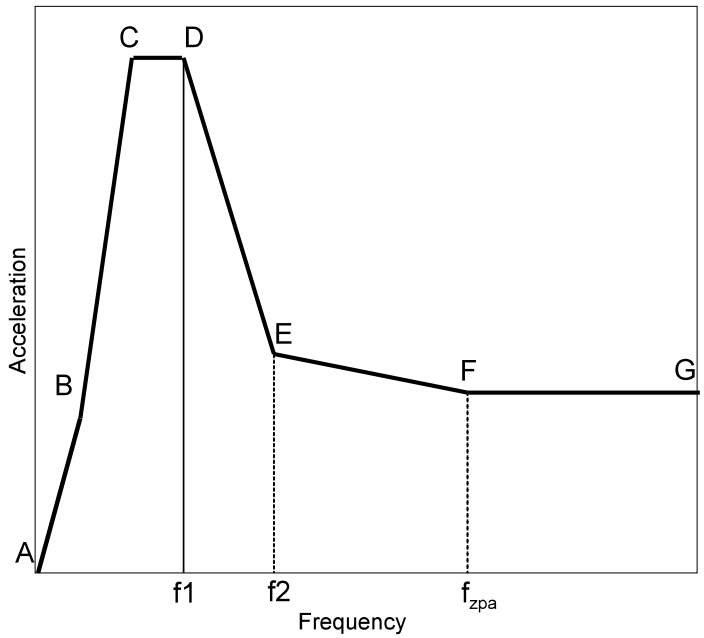

Figure 2. A narrow-banded response spectrum

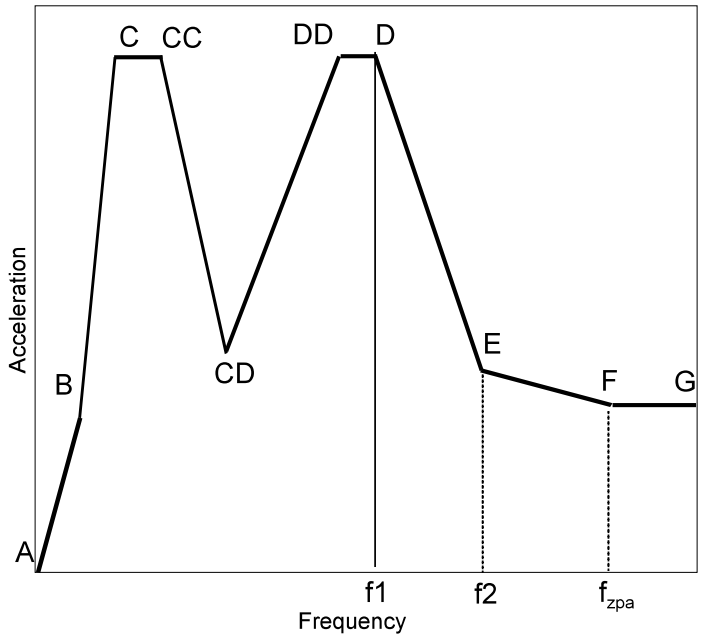

Figure 3. A multiple narrow-banded response spectrum

Research since the 1980s (e.g., Refs. 12, 13, and 14) has shown that between the end of the region of amplified spectral acceleration, D, and the beginning of the rigid region, E, in Figure 1, the modal response consists of both the periodic and rigid components. Appropriate methods, as discussed in Regulatory Position C.1.3, should be used to separate the two components in this transition region. The periodic components of modal responses are combined with the other periodic modal responses in accordance with Regulatory Position C.1.1; the rigid components of modal responses are combined with the other rigid responses in accordance with Regulatory Position C.1.2.

Finally, after calculating the total periodic response, total rigid response, and residual rigid response, an appropriate combination method, as discussed in Regulatory Position C.1.5, should be used to obtain the total response.

Combination of Spatial Components

Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants" (Ref. 15), specifies that the design of all Seismic Category 1 SSCs should be based on three orthogonal components (two horizontal and one vertical) of a prescribed design earthquake motion.

Regulatory Position C.2 of this guide, for the combination of spatial components, is the same as in Revision 1 of this guide, with one notable addition. When using the response spectrum method, use of the 100-40-40 percent combination rule proposed by Newmark (Ref. 16), as described in Regulatory Position C.2.1 of this guide, is acceptable as an alternative to the SRSS method.

Response Spectrum Method

For response spectrum analysis, in which each of the three spatial components are calculated separately, Chu, Amin, and Singh (Ref. 17) concluded that for an SCC subjected to the action of the three components of an earthquake motion, the representative maximum response of interest of the SSC can be satisfactorily obtained by taking the SRSS of the corresponding representative maximum response for each of the three components calculated separately.

The SRSS procedure for combining the responses to the three components of an earthquake motion is based on the consideration that it is very unlikely that the maximum response for each of the three spatial components would occur at the same time during an earthquake.

The 100-40-40 percent rule was originally proposed as a simple way to estimate the maximum expected response of a structure subject to three-directional seismic loading for response spectrum analysis, and is the only alternative method for spatial combination that has received any significant attention in the nuclear power industry. The results of the 100-40-40 spatial combination have been compared with the SRSS spatial combination. Generally, they indicate that the 100-40-40 combination method produces higher estimates of maximum response than the SRSS combination method by as much as 16 percent, while the maximum under-prediction is 1 percent.

Time History Method

When using the time history method, the representative maximum response of interest of the SSC can be obtained either by performing separate analyses for each of the three components of earthquake motion, or by performing a single analysis with all three components of earthquake motion applied simultaneously. In the latter case, the three components of earthquake must be statistically independent (Ref. 18).

C. REGULATORY POSITION

This guide (Revision 2) describes methods that the NRC staff considers acceptable to account for knowledge gained by research conducted in the United States since Revision 1 of this guide was issued in 1976. The more conservative methods of combining modal responses (as described in Revision 1) remain acceptable. However, if applicants for new licenses choose to use Revision 1 methods for combining modal responses, their analyses should address the residual rigid response of the missing mass modes (as discussed in Regulatory Positions C.1.4.1 and C.1.5.1 of this guide). Licensees of existing operating plants are also encouraged to consider the residual rigid response of the missing mass modes in their seismic analyses of SSCs (as discussed in Regulatory Positions C.1.4.1 and C.1.5.1) when they choose to use Revision 1 methods for combining modal responses, because doing so will produce more accurate results.

1. Combination of Individual Modal Responses

1.1 Combination of Periodic Modal Responses

Research since the late 1970s has shown that in the regions of amplified spectral displacement, amplified spectral velocity, and amplified spectral acceleration of a spectrum (regions AB, BC, and CD in Figure1), the periodic responses are dominant. Beyond amplified spectral acceleration region CD and up to E, the modal responses consist of both the periodic and rigid components. (Refer to Chapter 3 of Reference 6 for a discussion of periodic and rigid responses, as well as periodic and rigid components of responses.) The periodic modal responses and the periodic components of modal responses are combined using the following double sum ["complete quadratic combination" (CQC)] equation:

$$R_{pI} = \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \varepsilon_{ij} R_{p_i} R_{p_j} \right]^{1/2} \qquad (1)$$

where R_{pI} = combined periodic response for the I^{th} component of seismic input motion (I = 1, 2, 3, for one vertical and two horizontal components), ϵ_{ij} = the modal correlation coefficient for modes i and j, R_{pi} = periodic response or periodic component of a response of mode i, R_{pj} = periodic response or periodic component of a response of mode j, and n = number of modes considered in the combination of modal responses.

For completely correlated modes i and j, $\epsilon_{ij} = 1$; for partially correlated modes i and j, $0 < \epsilon_{ij} < 1$; for uncorrelated modes i and j, $\epsilon_{ij} = 0$.

The modal correlation coefficients are uniquely defined, depending on the method chosen for evaluating the correlation coefficient, as follows.

1.1.1 *Square Root of the Sum of the Squares (SRSS) Method*

At the foundation of all methods for combining uncorrelated modal responses is the SRSS method. All methods for combination of periodic modal response components are equivalent to the SRSS method if the frequencies of the modes are all sufficiently separated. In this case,

$\epsilon_{ij} = 1.0$ for $i = j$

and

$\epsilon_{ij} = 0.0$ for $i \neq j$

and Equation 1 reduces to the following:

$$R_{pI} = \left[\sum_{i=1}^{n} R_{p_i}^{\,2}\right]^{1/2} \tag{2}$$

If modes with closely spaced frequencies exist, the SRSS method is not applicable, and one of the two methods in Regulatory Positions C.1.1.2 and C.1.1.3 (below) should be used instead. The definition of modes with closely spaced frequencies is a function of the critical damping ratio (Ref. 5, page 66):

(1) For critical damping ratios ≤2%, modes are considered closely spaced if the frequencies are within 10% of each other (i.e., for $f_i < f_j$, $f_j \leq 1.1 f_i$).

(2) For critical damping ratios >2%, modes are considered closely spaced if the frequencies are within five times the critical damping ratio of each other (i.e., for $f_i < f_j$ and 5% damping, $f_j \leq 1.25 f_i$; for $f_i < f_j$ and 10% damping, $f_j \leq 1.5 f_i$).

1.1.2 *Rosenblueth Correlation Coefficient*

Rosenblueth (Ref. 8) provided the first significant mathematical approach to the evaluation of modal correlation for seismic response spectrum analysis. It is based on the application of random vibration theory, utilizing a finite duration of white noise to represent seismic loading. A formula for calculation of the coefficient ϵ_{ij} as a function of modal frequencies (f_i, f_j), modal damping ratios (λ_i, λ_j), and the time duration of strong earthquake motion (t_D) was derived as follows:

$$\varepsilon_{ij} = \left[1 + \left(\frac{f'_i - f'_j}{\lambda'_i f_i + \lambda'_j f_j}\right)^2\right]^{-1} \tag{3}$$

where

$$f'_i = f_i\left[1 - \lambda_i^2\right]^{1/2}$$

$$\lambda_i' = \lambda_i + \frac{1}{\pi t_D f_i}$$

and f_j' , λ_j' are similarly defined.

Appendix D to Reference 5 tabulates numerical values of ϵ_{ij} for the Rosenblueth formula as a function of frequency, frequency ratio, and strong motion duration time for constant modal damping of 1%, 2%, 5% and 10%. The effect of t_D is most significant at 1% damping and low frequency. For 5% and 10% damping, t_D = 10 sec. and 1,000 sec. produced similar values for ϵ_{ij} regardless of frequency. The most significant result is that ϵ_{ij} is highly dependent on the damping ratio; for 2%, 5%, and 10% damping, ϵ_{ij} = 0.2, 0.5, and 0.8, respectively, at a frequency ratio of 0.9 (modal frequencies within 10%).

1.1.3 *Der Kiureghian Correlation Coefficient*

Der Kiureghian (Ref. 9) presents an expression for ϵ_{ij} similar to Rosenblueth's. It is also based on the application of random vibration theory, but utilizes an infinite duration of white noise to represent seismic loading. A formula for calculation of the coefficient ϵ_{ij} as a function of modal frequencies (f_i, f_j) and modal damping ratios (λ_i, λ_j) was derived as follows:

$$\varepsilon_{ij} = \frac{8\left(\lambda_i \lambda_j f_i f_j\right)^{1/2}\left(\lambda_i f_i + \lambda_j f_j\right) f_i f_j}{\left(f_i^2 - f_j^2\right)^2 + 4\lambda_i \lambda_j f_i f_j\left(f_i^2 + f_j^2\right) + 4\left(\lambda_i^2 + \lambda_j^2\right) f_i^2 f_j^2} \qquad (4)$$

While the form of Equation 4 differs significantly from that of Equation 3, the two equations produce equivalent results if t_D is assumed to be very large in Equation 3. This is shown in Appendix D to Reference 5, where ϵ_{ij} is tabulated for the Rosenblueth formula (with t_D = 1,000 sec.) and the Der Kiureghian formula.

1.2 Combination of Rigid Modal Responses

In the high-frequency regions (regions EF and FG in Figure 1), the rigid responses predominate. Also, beyond the amplified acceleration region of CD and up to E in Figure 1, the modal responses consist of both periodic and rigid components.

The rigid responses and rigid components of responses are combined algebraically, as follows:

$$R_{rI} = \sum_{i=1}^{n} R_{ri} \qquad (5)$$

where R_{rI} = combined rigid response for the I^{th} component of seismic input motion (I =1, 2, 3, for one vertical and two horizontal components), R_{ri} = rigid response or rigid component of a response of mode i, and n = number of modes considered in the combination of modal responses.

1.3 Modes with Both Periodic and Rigid Response Components

Beyond the amplified acceleration region of CD and up to E in Figure 1, the modal responses consist of both the periodic and rigid components. Several methods were examined for the separation of periodic and rigid response components (Ref. 5). The Gupta method (Refs. 12, 13, and 19) and Lindley-Yow method (Ref. 14) are considered acceptable by the NRC staff, subject to the limitations discussed below. For the I^{th} direction of seismic input motion, the periodic components of modal responses obtained in this section should be combined with the other periodic modal responses (or periodic components of modal responses) using Equation 1. Similarly, for the I^{th} direction of seismic input motion, the rigid components of modal responses obtained in this section should be combined with the other rigid modal responses (or rigid components of modal responses) using Equation 5.

1.3.1 *Gupta Method*

Gupta separated the periodic and rigid components of a response by a rigid response coefficient α_i. Using the notations in Regulatory Positions C.1.1 and C.1.2 above, the rigid response component of a modal response, R_i , is defined as follows:

$$R_{r_i} = \alpha_i R_i \tag{6.1}$$

The periodic response component of R_i can then be expressed as follows:

$$R_{p_i} = \left[1-\alpha_i^2\right]^{1/2} R_i, \qquad \text{where} \quad R_i^2 = R_{p_i}^2 + R_{r_i}^2 \tag{6.2}$$

With proper selection of key frequencies *f1* and *f2*, Gupta determined that the rigid response coefficient, α_i, can be idealized as follows:

$$\alpha_i = \frac{\ln\left(f_i/f1\right)}{\ln\left(f2/f1\right)}, \qquad f1 \le f_i \le f2 \tag{7.1}$$

and

$$\alpha_i = 0 \text{ for } f_i \le f1, \qquad \alpha_i = 1 \text{ for } f_i \ge f2$$

Gupta expressed the key frequencies *f1* and *f2* as follows:

$$f1 = \frac{S_{a_{\max}}}{2\pi S_{v_{\max}}}, \quad \text{and } f2 = fr \tag{7.2}$$

where $S_{a\,max}$ = the maximum spectral acceleration, $S_{v\,max}$ = the maximum spectral velocity, *fr* = the rigid frequency. *fr* is the lowest frequency at which the responses of single degree of freedom (SDOF) oscillators become completely correlated with the input motion (i.e., α_i =1 for all $f_i \ge fr$).

Gupta has postulated that *fr* can be identified as the frequency where response spectral curves for different damping values converge, and that above this frequency, the periodic component of the modal response is essentially zero. It was found (Ref. 5) that when using Gupta's method, the results of combining modal responses are somewhat sensitive to the value of *f2* used, and there are situations that *f2* may not be uniquely determined by postulating convergence of spectral curves of different damping values. In such cases, Appendix B to this guide recommends a more systematic method to determine *f2*, as first proposed in Appendix F to Reference 5.

The definition *of f2* in Equation 7.2 (above) is applicable to all types of response spectra (broad-banded, narrow-banded, or multiple narrow-banded).

The definition of *f1* in Equation 7.2 (above) is applicable to single-peaked, unbroadened spectra. When the spectral peak has been broadened ±15% to account for uncertainty, as shown in Figure 2, it is acceptable to select *f1* at point D in Figure 2. The staff will review alternative *f1* selections on a case-by-case basis.

For multiple-peaked, narrow-banded spectra, as shown in Figure 3, the selection of *f1* is not straightforward, because there is more than one frequency region of the spectrum that exhibits significant amplification above the ZPA, due to predominantly periodic response. To avoid possible overestimation of the rigid response component in this higher frequency, amplified response region, an acceptable approach is to select the highest frequency of all significant peaks as *f1*, such as point D in Figure 3. Alternative selection of *f1* will be reviewed by the staff on a case-by-case basis.

For broad-banded spectra, as shown in Figure 1, typical of a design ground spectrum or a design spectral envelope of multiple in-structure response spectra, an acceptable approach is to select *f1* at point D in Figure 1. The staff will review alternative *f1* selections on a case-by-case basis.

1.3.2 *Lindley-Yow Method*

In the Lindley-Yow method, separate analyses are performed for periodic and rigid response components. The periodic response component is calculated as follows:

$$R_{p_i} = R_i \left[\overline{S_{a_i}} / S_{a_i} \right] \tag{8.1}$$

where a modified spectral acceleration is used and defined as follows:

$$\overline{S_{a_i}} = \left[S_{a_i}^2 - ZPA^2 \right]^{1/2}, \qquad \overline{S_{a_i}} \geq 0 \tag{8.2}$$

where $S_{a\,i}$ = spectral acceleration of mode *i*, and *ZPA* = zero period acceleration, which is the maximum acceleration of the base input time history record.

Employing Gupta's notations, the rigid response component is calculated using the following definition for the rigid response coefficient:

$$\alpha_i = ZPA / S_{a_i}, \qquad 0 \le \alpha_i \le 1 \tag{9}$$

The rigid response component is calculated in accordance with Equation 6.1, while the periodic response component is calculated in accordance with either Equation 6.2 or Equation 8.1.

There is one limitation on the use of Lindley-Yow's method. Specifically, Equation 9 gives $\alpha_i = 1$ when $Sa_i = ZPA$ at f_{zpa} (the ZPA frequency) and higher frequencies. It has its minimum value at the spectral acceleration peaks (C–D in Figure 2, C–CC and DD–D in Figure 3), where the modified spectral acceleration from Equation 8.2 is essentially equal to the spectral acceleration. However, at frequencies below point C in Figures 2 and 3, α_i begins to increase and would exceed 1.0 for $Sa_i < ZPA$. Therefore, Lindley-Yow's method should not be used for SSCs that have natural frequencies less than the frequency of the lowest-frequency spectral acceleration peak (point C in Figures 2 and 3), unless it is modified to set $\alpha_i = 0$ for frequencies below point C.

1.4 Residual Rigid Response

Unlike tall buildings and other relatively flexible systems, nuclear power plant SSCs may have important natural vibration modes at frequencies higher than the ZPA frequency, f_{zpa}. In most cases, it is not practical to accurately calculate these high-frequency modes, which are not excited by the seismic ground or in-structure motion. If only modes with frequencies below f_{zpa} are included in the dynamic analysis, the mass associated with the modes with frequencies higher than f_{zpa} has not been included in (i.e., is "missing" from) the dynamic analysis. It is important to account for the residual rigid response if a nuclear power plant SSC has significant natural vibration modes at frequencies higher than f_{zpa}. Ignoring the residual rigid response in these cases may result in underestimation of some SSC element forces and moments in the vicinity of supports, as well as underestimation of some support forces and moments (e.g., Ref. 10). The residual rigid response of the missing mass modes (or the "missing mass response") can be calculated using the Missing Mass method of Kennedy (Ref. 10) or the Static ZPA method. These two methods, which were examined in Reference 5, have been selected as providing acceptable results as noted below.

Use of the Missing Mass method for calculating the contribution of high frequency modes is acceptable for both response spectrum analysis and modal superposition time history analysis. In modal superposition time history analysis, a procedure analogous to the approach used in Combination Method A (see Regulatory Position 1.4.1) for response spectrum analysis is acceptable. Only modes with $f < f_{zpa}$ participate in the modal solution; the missing mass contribution, scaled to the instantaneous input acceleration, is treated as an additional mode in the algebraic summation of modal responses at each time step. The missing mass contribution is considered for all degrees of freedom.

1.4.1 *Missing Mass Method*

The Missing Mass method (Ref. 10) is a convenient, computationally efficient and accurate method for the following uses:

(1) Account for the contribution of all modes with frequencies above the frequency (f_{zpa}) at which the response spectrum returns to the zero period acceleration (ZPA).

(2) Account for the contribution to support reactions of mass that is apportioned to system support points.

The Missing Mass method constitutes the total effect of all system mass that is not included in the modes with frequencies below f_{zpa}. The system response to the missing mass is calculated by performing a static analysis for an applied load that equals the missing mass multiplied by the spectrum ZPA. This method is considered the only acceptable method to account for high-frequency modal contributions ($f \geq f_{zpa}$) and the effects of mass apportioned to system support points.

Kennedy (Ref. 10) documented this method and recommended including it in regulatory guidance. The mathematical details are presented in References 6 and 19, while the mathematical formulation is included as Appendix I to Reference 5 and is reproduced as Appendix A to this guide.

The guideline provided in References 10 and 19, that the missing mass contribution needs to be considered only if the fraction of missing mass at any degree of freedom exceeds 0.1, is non-conservative and should not be used. This guideline does not consider the total mass that is missing, which, in the limit, could be 10%. In a static analysis, this represents a 10% reduction in the applied load. The missing mass contribution should be calculated in all response spectrum analyses because its potential effect on support reactions is difficult to judge based on the fraction of missing mass. This calculation has been automated in a number of piping analysis codes and does not represent a significant computational effort.

The missing mass contribution to the response spectrum analysis solution represents response that is completely in-phase with the time-varying acceleration input and can be scaled to the instantaneous acceleration to obtain its contribution at any specific point in time. This characteristic is not important in response spectrum analysis because only peak response is predicted. In this case, the ZPA is used to calculate the missing mass contribution. However, the importance of the missing mass contribution is not limited to response spectrum analyses alone. Mode superposition time-history analysis is most accurately and efficiently performed by a procedure similar to that employed in response spectrum analysis (Ref. 6). Only modes that vibrate at frequencies below f_{zpa} need to be included in the transient mode superposition solution. The missing mass contribution, scaled to the instantaneous acceleration, is then algebraically summed with the transient solution at the corresponding time to obtain the total solution. This method is more rigorous and accurate than including additional modes in the transient mode superposition solution. Even if additional modes are included, it is still necessary to calculate the missing mass for the excluded, higher frequency modes and system support points.

1.4.2 *Static ZPA Method*

The Lindley-Yow method (Ref. 14) defines the acceleration of the rigid response component of all modes to be the ZPA of the response spectrum. The algebraic summation of the rigid response components for all modes (R_{rI}) is equivalent to the static response for a load equal to the total mass times the ZPA. When using the Lindley-Yow method, an alternative approach to including the contribution of high-frequency ($f \geq f_{zpa}$) modes is to calculate R_{rI} directly by the Static ZPA method. This eliminates the need for calculation of the missing mass, since it is automatically included in the static analysis of total mass times ZPA. The periodic response component (R_{pI}) is calculated in accordance with the Lindley-Yow method.

1.5 Complete Solution for Response Spectrum Analysis

Two methods are acceptable for obtaining the complete (periodic plus rigid) response spectrum analysis solution for each of the three orthogonal component motions (two horizontal and one vertical) of a prescribed design earthquake. The coefficients ϵ_{ij} in each method are determined by one of the combination methods for periodic modal responses (see Regulatory Position C.1.1).

The Lindley-Yow method is not suitable for analysis of systems with significant low-frequency response ($f < f_{spectral\ peak}$), unless the low-frequency correction is implemented (see Regulatory Position C.1.3.2).

The contribution of high-frequency modes ($f \geq f_{zpa}$) should be included in all response spectrum and modal superposition time history analyses. (See Regulatory Position C.1.4.)

1.5.1 *Combination Method A*

Combination Method A introduces the concept of periodic and rigid modal response components for the amplified modes ($f < f_{zpa}$). Mathematically, the complete solution is represented as follows:

$$R_{p_i} = \left[1 - \alpha_i^2\right]^{1/2} R_i$$

$$R_{r_i} = \alpha_i R_i$$

$$R_{pI} = \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \varepsilon_{ij} R_{p_i} R_{p_j} \right]^{1/2}, \quad \text{where } n = \text{number of modes below } f_{zpa} \qquad (10)$$

$$R_{rI} = \sum_{i=1}^{n} R_{r_i} + R_{Missing Mass I}$$

$$R_I = \left[R_{rI}^2 + R_{pI}^2\right]^{1/2}$$

where $R_{Missing\ Mass\ I}$ is the residual rigid response of the missing mass modes for the I^{th} component of seismic input motion (I = 1, 2, 3, for one vertical and two horizontal components), calculated by using the missing mass method described in Regulatory Position C.1.4.1.

Combination Method A is equally applicable to both the Lindley-Yow and Gupta methods (Regulatory Position C.1.3, "Modes with Both Periodic and Rigid Response Components"). Only the definition of α_i changes. It is to be noted that when using Revision 1 of this guide for combining modal responses, R_{ri} terms are all identically zero.

1.5.2 *Combination Method B*

Combination Method B is to be used only when implementing Regulatory Positions C.1.3.2 and C.1.4.2. This method utilizes the Static ZPA method to calculate R_{rI}. Combination Method B is completely compatible with the Lindley-Yow method only when the low frequency correction (see Regulatory Position C.1.3.2) is ***not*** necessary, because calculation of R_{rI} by the Static ZPA method is based on the Lindley-Yow definition for α_i, using Equation 9.

However, use of Combination Method B is acceptable even when using the low-frequency correction, because the predicted response will always be more conservative than Combination Method A.

Mathematically, the complete solution is represented as follows:

$$R_{p_i} = \left[1 - \alpha_i^2\right]^{1/2} R_i$$

$$R_{pI} = \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \varepsilon_{ij} R_{p_i} R_{p_j} \right]^{1/2}, \quad \text{where } n = \text{number of modes below } f_{zpa} \tag{11}$$

$$R_{rI} = R_{\ StaticZPA\ I}$$

$$R_I = \left[R_{rI}^2 + R_{pI}^2\right]^{1/2}$$

where $R_{\ StaticZPA\ I}$ is the rigid response for the I^{th} component of seismic input motion (I = 1, 2, 3, for one vertical and two horizontal components), calculated by using the static ZPA method described in Regulatory Position C.1.4.2.

2. Combining Effects Caused by Three Spatial Components of an Earthquake

Depending on which basic method is used in the seismic analysis (i.e., response spectra or time history method), the following two approaches are considered acceptable for the combination of three-dimensional earthquake effects.

2.1 Response Spectra Method

When the response spectra method is used, the representative maximum earthquake-induced response of interest in an SSC should be obtained by the SRSS combination of the maximum representative responses from the three earthquake components calculated separately as follows:

$$R = \left[\sum_{I=1}^{3} R_I^2 \right]^{1/2} \tag{12}$$

Where R = any response of interest of an SSC, R_I = combined response for the I^{th} component of seismic input motion (I = 1, 2, 3 for one vertical and two horizontal components), as obtained from Equations 10 or 11.

As an alternative, the 100-40-40 percent combination rule proposed by Newmark (Ref. 16) may be used in lieu of the SRSS method. The 100-40-40 procedure is as follows:

(1) Let R_1, R_2, R_3, be the maximum responses of an SSC caused by each of the three earthquake components calculated separately, such that

$$|R_1| \geq |R_2| \geq |R_3|$$

(2) The maximum seismic response attributable to earthquake loading in three orthogonal directions is given by the following equation:

$$R = (1.0|R_1| + 0.4|R_2| + 0.4|R_3|) \tag{13}$$

2.2 Time History Method

When time history analysis method is employed for seismic analyses, two types of analyses are generally performed:

(1) For time history analysis when each of the three spatial components are calculated separately, the representative maximum response of interest of an SSC can be satisfactorily obtained by taking the SRSS of the maximum responses from the time history analysis for each of the three earthquake components:

$$R = \left[\sum_{I=1}^{3} R_I^2 \right]^{1/2} \tag{14}$$

(2) If the three components of earthquake motion are statistically independent (e.g., Ref. 18), the maximum response of interest of an SSC can be obtained from algebraic summation of the three component responses at each time step.

When the effect of all three components of earthquake motion is calculated simultaneously, in a single dynamic analysis, algebraic summation is automatically achieved.

When the effect of each component of earthquake motion is calculated in a separate dynamic analysis, algebraic summation is obtained as follows:

$$R(t) = \sum_{I=1}^{3} R_I(t) \tag{15}$$

After algebraic summation at each time step, it is necessary to search the entire response time history, in order to find the maximum response. Because the time of maximum response may vary from location to location within the SSC, and also may vary for different responses at the same location (e.g., stresses vs. deflections), this process is carried out for each response of interest.

When using algebraic summation, it is important that the response of interest be consistent with the structural acceptance criterion. For example, an acceptance criterion for a beam-type structural member may be the maximum allowable axial stress, which is composed of a component attributable to axial force and two components attributable to bending moments. In this case, the response of interest would be the maximum axial stress, not the maximum axial force and maximum moment responses.

3. Methods Used

If the applicant has used the methods described in this guide, each applicable section of the safety analysis report (SAR) should state specifically which acceptable methods were used in analyzing the SSCs covered by that section.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this guide. No backfitting is intended or approved in connection with the issuance of this guide.

This revision identifies improved methods that the NRC staff considers acceptable for combining modal responses and spatial components in seismic response analysis for the design of Category I SSCs. The more conservative methods for combining modal responses identified in Revision 1 of this guide also remain acceptable. However, if applicants for new licenses choose to use Revision 1 methods for combining modal responses, their analyses should address the residual rigid response of the missing mass modes (as discussed in Regulatory Positions C.1.4.1 and C.1.5.1 of this guide). Licensees of existing operating plants are also encouraged to consider the residual rigid response of the missing mass modes in their seismic analyses of SSCs (as discussed in Regulatory Positions C.1.4.1 and C.1.5.1) when they choose to use Revision 1 methods for combining modal responses, because doing so will produce more accurate results.

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REGULATORY ANALYSIS

1. Statement of the Problem

The U.S. Nuclear Regulatory Commission (NRC) issued Revision 1 of Regulatory Guide 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis," in February 1976 to describe acceptable methods for complying with the NRC's regulations governing the seismic analysis and design of nuclear power plant structures, systems, and components (SSCs) that are important to safety. Since the issuance of Revision 1 of Regulatory Guide 1.92 in 1976, research in the United States has resulted in improved methods for combining modal responses and spatial components that provide more accurate estimates of SSC seismic response, while reducing unnecessary conservatism. This guide (Revision 2) describes methods that the NRC staff considers acceptable in view of those improvements.

2. Objectives

The objective of the regulatory action is to update the NRC's guidance in the area of seismic analysis and design of nuclear power plant SSCs in order to give licensees and applicants an opportunity to use state-of-the-art methods that are available in one document.

3. Alternatives and Consequences of the Proposed Action

3.1 Alternative 1: Do Not Revise Regulatory Guide 1.92

Under this alternative, the NRC would not revise Regulatory Guide 1.92 and licensees would continue to rely on the current version (Revision 1), which is based on technology developed in the 1970s. This alternative is considered the baseline or "no-action" alternative.

3.2 Alternative 2: Update Regulatory Guide 1.92

Under this alternative, the NRC would update Regulatory Guide 1.92 to reflect improved methods for combining modal responses and spatial components that provide more accurate estimates of SSC seismic response, while reducing unnecessary conservatism. The staff has identified the following consequences associated with adopting Alternative 2:

(1) Licensees would have guidance on the use of the latest technology available, with consequent improvements in the seismic analysis and design of SSCs. The more conservative methods for combining modal responses in Revision 1 of this guide would remain acceptable. However, if applicants for new licenses choose to use Revision 1 methods for combining modal responses, their analyses should address the residual rigid response of the missing mass modes (as discussed in Regulatory Positions C.1.4.1 and C.1.5.1 of this guide). Licensees of existing operating plants are also encouraged to consider the residual rigid response of the missing mass modes in their seismic analyses of SSCs (as discussed in Regulatory Positions C.1.4.1 and C.1.5.1) when they choose to use Revision 1 methods for combining modal responses, because doing so will produce more accurate results. The cost and effort to address the residual rigid response effect are considered an insignificant part of the overall effort for the seismic design of an SSC, as no extensive computer calculation is expected. Previous analyses need not be repeated, since the seismic design process used for the existing operating plants, including Revision 1 of this guide, contain ample conservatism, such that the omission of the residual rigid response effect is not expected to raise any safety concern for the seismic design of SSCs for these plants.

(2) Regulatory efficiency would be improved by reducing uncertainty as to what is acceptable and by encouraging consistency in the seismic analysis and design of SSCs. Benefits to the industry and the NRC will accrue to the extent this occurs. NRC reviews would be facilitated because licensee submittals would be more predictable and analytically consistent.

(3) Both the NRC and the nuclear industry would realize cost savings. From the NRC's perspective, relative to the baseline, the NRC will incur one-time incremental costs to issue the revised regulatory guide. However, the NRC should also realize cost savings associated with the review of licensee submittals. In the staff's view, the ongoing cost savings associated with these reviews should more than offset the one-time cost.

On balance, the NRC staff expects that industry would realize a net savings, as their one-time incremental cost to review and comment on the revised regulatory guide would be more than compensated for by the efficiencies (e.g., reduced unnecessary conservatism, followup questions, and revisions) associated with each licensee submission.

4. Conclusion

Based on this regulatory analysis, the staff recommends that the NRC should revise Regulatory Guide 1.92. The staff concludes that the proposed action will reduce unnecessary burden on the part of both the NRC and its licensees, while improving the process for seismic analysis and design of safety-related SSCs. Furthermore, the staff sees no adverse effects associated with revising Regulatory Guide 1.92.

BACKFIT ANALYSIS

This regulatory guide gives licensees and applicants an opportunity to use state-of-the-art methods that are available in one document. As such, this revision of Regulatory Guide 1.92 does not require a backfit analysis as described in 10 CFR 50.109(c), because it does not impose a new or amended provision in the Commission's rules or a regulatory staff position interpreting the Commission's rules that is either new or different from a previous applicable staff position. In addition, this regulatory guide does not require modification or addition to structures, systems, components, or design of a facility or the procedures or organization required to design, construct, or operate a facility. Rather, a licensee or applicant is free to select a preferred method for achieving compliance with a license or the rules or orders of the Commission as described in 10 CFR 50.109(a)(7). The more conservative methods for combining modal responses in Revision 1 of this guide remain acceptable. However, if applicants for new licenses choose to use Revision 1 methods for combining modal responses, their analyses should address the residual rigid response of the missing mass modes (as discussed in Regulatory Positions C.1.4.1 and C.1.5.1 of this guide). Licensees of existing operating plants are also encouraged to consider the residual rigid response of the missing mass modes in their seismic analyses of SSCs (as discussed in Regulatory Positions C.1.4.1 and C.1.5.1) when they choose to use Revision 1 methods for combining modal responses, because doing so will produce more accurate results. It is the staff's judgment that there is ample conservatism in the seismic design process for the existing operating plants (including Revision 1 of this guide), such that the omission of the residual rigid response effect is not expected to raise any safety concern for the seismic design of SSCs for these plants.

APPENDIX A

CALCULATION OF MISSING MASS CONTRIBUTION TO TOTAL RESPONSE

(From Appendix I to Reference 5)

Mathematical descriptions of the "missing mass" contribution to total response are contained in References 5, 6, and 10, while Reference 10 presents a step-by-step, mechanistic approach. Reference 6 presents a more complete mathematical description, which provides additional insight, and Reference 5 essentially incorporates that mathematical description. It is recommended that Section 3.4 of Reference 6 be reviewed to attain an understanding of the procedure.

The following steps can be utilized to calculate the response contribution of all system modes of vibration with frequencies equal to or greater than f_{zpa}. (Note that each direction of earthquake input motion must be considered separately.)

Step1. Determine the modal responses only for those modes with natural frequencies less than that at which the spectral acceleration approximately returns to the ZPA (f_{zpa}).

Step2. For each degree-of-freedom (DOF) included in the dynamic analysis, determine the fraction of DOF mass included in the summation of all modes included in Step 1. This fraction d_i for each DOF i is given by the following equation:

$$d_i = \sum_{n=1}^{N} \left[\left(c_{n,j} \right) \left(\phi_{n,i} \right) \right] \tag{A.1}$$

where

n = mode number ($1, 2, \ldots, N$)
N = the number of modes included in Step 1
$\phi_{n,i}$ = eigenvector value for mode n and DOF i
j = direction of input motion
$c_{n,j}$ = participation factor for mode n in the j^{th} direction:

$$c_{n,j} = \frac{\left\{ \phi_n \right\}^T [m] \left\{ \delta_{ij} \right\}}{\left\{ \phi_n \right\}^T [m] \left[\phi_n \right]} \tag{A.2}$$

where δ_{ij} is the Kronecker delta, which is 1 if DOF i is in the direction of the earthquake input motion j and 0 if DOF i is a rotation or not in the direction of the earthquake input motion j. This assumes that the three orthogonal directions of earthquake input motion are coincident with the DOF directions. Also, [m] is the mass matrix.

Next, determine the fraction of DOF mass not included in the summation of these modes:

$$e_i = d_i - \delta_{ij} \tag{A.3}$$

Step3 Higher modes can be assumed to respond in phase with the ZPA and, thus, with each other; hence, these modes are combined algebraically, which is equivalent to pseudostatic response to the inertial forces from these higher modes excited at the ZPA. The pseudostatic inertial forces associated with the summation of all higher modes for each DOF *I* are given by the following:

$$P_i = (ZPA)(M_i)(e_i) \tag{A.4}$$

where P_i is the force or moment to be applied at DOF i, M_i is the mass or mass moment of inertia associated with DOF i.

The structure is then statically analyzed for this set of pseudostatic inertial forces applied to all degrees of freedom to determine the maximum responses associated with high-frequency modes not included in Step 1.

This procedure requires the computation of individual modal responses only for lower-frequency modes. Thus, the more difficult higher-frequency modes need not be determined. The procedure ensures inclusion of all modes of the structural model and proper representation of DOF masses.

APPENDIX B

ALTERNATIVE METHOD FOR DETERMINATION OF THRESHOLD FREQUENCY FOR RIGID MODAL RESPONSE

(From Appendix F to Reference 5)

This appendix presents an alternative method for determining the threshold frequency for rigid modal response (*f2* in Gupta's method, Regulatory Position C.1.3.1 of this guide), which was first proposed in Appendix F to Reference 5.

During the generation of a response spectrum from a ground or in-structure time history record, the complete time history of each single degree of freedom (SDOF) oscillator response is calculated and processed to identify the peak response. This peak response becomes a single point on the response spectrum plot. Each SDOF oscillator peak response has an associated time of occurrence and direction of the peak response, although this information is typically not retained because it is not needed in the generation of response spectrum. Nonetheless, valuable conclusions can be derived by comparing this information to the time and direction of the peak acceleration from the input time history record.

The lowest SDOF oscillator frequency (*f2* in Gupta's method) for which the time and direction of peak response coincide with the time and direction of the peak of the input time history represents the onset of rigid modal response that is in-phase with the input, provided that all higher-frequency SDOF oscillators exhibit the same behavior (i.e., for $f \geq f2$, all SDOF oscillator peak responses occur at the same time and in the same direction as the peak of the input time history). To further verify that rigid modal response exists, a comparison of the crossings of the acceleration equal to zero datum between the input time history and SDOF oscillator time history response should be performed for SDOF oscillator frequencies in the vicinity of *f2*.

The calculation of *f2*, for each critical damping ratio of interest, can be fully automated and made a part of the response spectrum generation algorithm.