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DRAFT REGULATORY GUIDE

Contact: O.P. Gormley (301)415-6793

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(Proposed Revision 2 of Regulatory Guide 1.92)

COMBINING MODAL RESPONSES AND SPATIAL COMPONENTS IN SEISMIC RESPONSE ANALYSIS

A. INTRODUCTION

This regulatory guide is being revised to improve the guidance to licensees and applicants on methods acceptable to the NRC staff for combining modal responses and spatial components in seismic response analysis in the design and evaluation of nuclear power plant structures, systems, and components important to safety.

Criterion 2, "Design Bases for Protection Against Natural Phenomena," of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," requires, in part, that nuclear power plant structures, systems, and components important to safety be designed to withstand the effects of natural phenomena such as earthquakes without loss of capability to perform their safety functions. Such structures, systems, and components are also 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 the implementation of 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, for either an operating license applicant or holder whose construction permit was issued before January 10, 1997, the earthquake engineering criteria in Section VI of Appendix A to 10 CFR Part 100 continue to apply.

This guide describes methods acceptable to the NRC staff for complying with the NRC's regulations with regard to:

1. Combining the values of the response of individual modes in a response spectrum modal dynamic analysis to find the representative maximum value of a particular response of interest for the design of a given element of a nuclear power plant structure, system, or component.

2. Combining the maximum values (in the case of time-history dynamic analysis) or the representative maximum values (in the case of spectrum dynamic analysis) of the response of a given element of a structure, system, or component, when such values are calculated independently for each of the three orthogonal spatial components (two horizontal and one vertical) of an earthquake. The combined value will be the representative maximum value of the combined response of that element of the structure, system, or component to simultaneous action of the three spatial components.

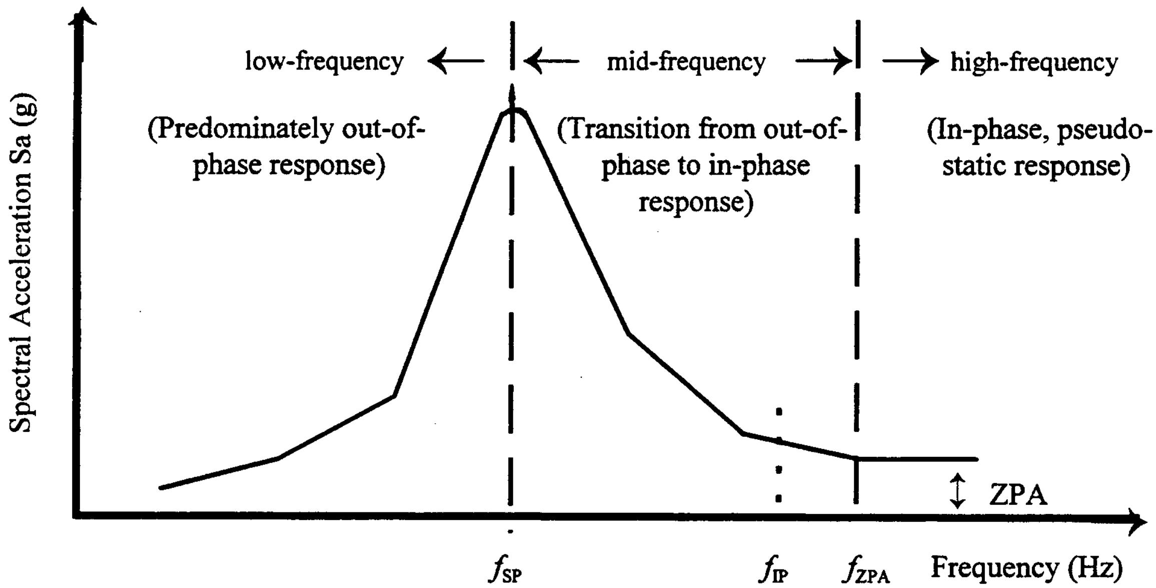
Regulatory guides are issued to describe to the public methods acceptable to the NRC staff for implementing specific parts of the NRC's regulations, to explain techniques used by the staff in evaluating specific problems or postulated accidents, and to provide guidance to applicants. Regulatory guides are not substitutes for regulations, and compliance with regulatory guides is not required. Regulatory guides are issued in draft form for public comment to involve the public in developing the regulatory positions. Draft regulatory guides have not received complete staff review; they therefore do not represent official NRC staff positions.

The information collections contained in this draft regulatory guide are covered by the requirements of 10 CFR Part 50, which were approved by the Office of Management and Budget, approval number 3150-0011. If a means used to impose an information collection does not display a currently valid OMB control number, the NRC may not conduct or sponsor, and a person is not required to respond to, the information collection.

B. DISCUSSION

BACKGROUND

The major application of seismic response spectrum analysis in the nuclear industry is for systems and components attached to building structures. Past practice has been to assume that individual modal responses in the mid-frequency region are out of phase, and that the combination methods applicable to the low-frequency region are also applicable to the mid-frequency region. Revision 1 of this guide presented methods for combining responses of modes that are closely spaced and those that are not closely spaced. This revision presents methods that have been developed by taking advantage of improvements in technology that allow a more accurate estimate to be made, thus eliminating unnecessary conservatism.



**Fi
gure 1 Idealized In-Structure Response Spectrum**

COMBINATION OF VALUES OF THE RESPONSE OF INDIVIDUAL MODES

Regulatory Position 1 of this guide presents methods for calculating independent peak modal responses and acceptable rules for combining them so as to predict peak dynamic response. The input response spectrum defines the acceleration to be applied to each natural mode of vibration of the structure, depending on its modal frequency.

NUREG/CR-6645, "Reevaluation of Regulatory Guidance on Modal Response Combination Methods for Seismic Response Spectrum Analysis" (Ref. 1), reports the results of an evaluation of recent developments for modal response combination conducted through a literature review and analytical effort that included analysis of a piping system model previously used in the development of NUREG/CR-5627, "Alternate Modal Combination Methods in Response Spectrum Analysis" (Ref. 2). The research was based on a distribution of spectral acceleration vs. frequency for a building-filtered in-structure response spectrum such as the idealized one shown in the following figure.

where:

f_{SP} = frequency at which the peak spectral acceleration is reached; typically the fundamental frequency of the building/soil system,

f_{ZPA} = frequency at which the spectral acceleration returns to the zero period acceleration (ZPA), and

f_{IP} = frequency above which the single degree of freedom (SDOF) modal responses are considered to be in phase with the time-varying input acceleration used to generate the response spectrum

The figure illustrates three basic phases: low frequency (out of phase), transition, and high frequency (in phase).

In the low-frequency region of the spectrum (< f_{SP}), the modal responses of SDOF oscillators are not in phase with the applied acceleration time history, and generally are not in phase with each other. These are designated "out-of-phase" modal responses, which indicates the response component is not in phase with the time-varying input acceleration. Since a response spectrum provides only peak acceleration vs. frequency, with no phasing information, the out-of-phase peak modal responses for a multi-modal structural system require a rule or methodology for combination. Based on the assumption that the peak modal responses are randomly phased, the square root of the sum of the squares (SRSS) method was adopted. Modifications to the SRSS method were subsequently developed in order to account for potential phase correlation when modal frequencies are numerically close (i.e., closely spaced modes). This revision to Regulatory Guide 1.92 recommends improved methods for combining the low-frequency response.

The high-frequency region of the spectrum (> f_{ZPA}) is characterized by no amplification of the peak acceleration of the input time history. A SDOF oscillator having a frequency > f_{ZPA} is accelerated in phase and with the same acceleration magnitude as the applied acceleration, at each instant in time (i.e., the response component is "in phase" with the time-varying input acceleration). A system or component with fundamental frequency > f_{ZPA} is correctly analyzed as a static problem subject to a loading equal to its mass times the ZPA. The system or component is said to respond "pseudo-statically." This concept can be extended to the high-frequency (> f_{ZPA}) modal responses of multi-modal systems or components. The mass not participating in the amplified modal responses (i.e., "missing mass") multiplied by the ZPA is applied in a static analysis to obtain the response contribution from all modes with frequencies > f_{ZPA}. This revision to Regulatory Guide 1.92 recommends improvements in the combination of responses in both the low- and high-frequency ranges.

In the mid-frequency region (f_{SP} to f_{ZPA}), it has been postulated that the peak SDOF oscillator modal responses consist of two distinct and separable elements. The first element is the out-of-phase response component and the second element is the in-phase response component. It is further postulated that there is an uninterrupted transition from out-of-phase response to in-phase response. If $f_{IP} < f_{ZPA}$ can be defined, the mid-frequency region can be further divided into two sub-regions: $f_{SP} < f_1 < f_{IP}$ and $f_{IP} \leq f_2 \leq f_{ZPA}$.

Past practice in the nuclear power industry has been to assume that individual modal responses in the mid-frequency region ($f_{SP} < f < f_{ZPA}$) are out of phase, and that the combination methods applicable to the low-frequency region are also applicable to the mid-frequency region. Improved approaches are addressed in the following sections. Three elements are needed to define a suitable methodology for the mid-frequency region:

1. A definition for f_{IP},

2. A method for separating the in-phase and out-of-phase components of individual peak modal responses, and

3. A phase relationship for combining the total out-of-phase response component with the total in-phase response component.

COMBINATION OF EFFECTS CAUSED BY THREE SPATIAL COMPONENTS OF AN EARTHQUAKE

Regulatory Position 2 of this guide, "Combination of Effects Caused by Three Spatial Components of an Earthquake," has not been changed from Revision 1 except to add a caution regarding correlation of ground motions and to endorse the 100-40-40 percent combination rule of the American Society of Civil Engineers (ASCE, Ref. 3), which preserves the mathematical sign when it is necessary to distinguish direction. The 100-40-40 percent rule is the only alternative method for spatial combination that has received any significant attention in the nuclear power industry. It 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.

The application of time-history analysis is expected to be minimal since the seismic input motions are typically applied simultaneously and the spatial combination technique requires that each direction meet a specified criterion of statistical independence. Therefore, the predominant use of spatial combination methods is for response spectrum analysis.

The spatial combination method (i.e., the method for combining the results of these analyses) depends on whether the three spatial components are calculated separately (independently) or simultaneously.

Response Spectrum Analysis

For response spectrum analysis when each of the three spatial components are calculated independently, Chu, Amin, and Singh (Ref. 4) concluded that the representative maximum value of a particular response of interest for design (e.g., stress, strain, moment, shear, or displacement) of a given element of a structure, system, or component subjected to the simultaneous action of the three components of the earthquake can be satisfactorily obtained by taking the SRSS of the corresponding representative maximum values of the spectrum response for each of the three components calculated independently.

The SRSS procedure used by Newmark (Ref. 5) and Chu, Amin, and Singh (Ref. 4) for combining the values of the response to the three components of an earthquake is based on the consideration that it is very unlikely that peak values of a response of a given element would occur at the same time during an earthquake. That is, the acceptance of the method of SRSS is based on the assumption of uncorrelated seismic ground motions.

The results of SRSS spatial combination have been compared with the 100-40-40 spatial combination. Generally they indicate that the 100-40-40 combination method produces higher estimates of maximum response than the SRSS combination method.

The results indicated that the 100-40-40 combination method is conservative by as much as 15%, when compared to the SRSS combination method, while the maximum under-prediction at this ratio is 1%. While this would seem to be a deterrent to the use of this method, the method becomes more attractive when it is necessary to maintain the directional-indicating mathematical sign that would be lost in the taking of squares of the values in the SRSS method.

C. REGULATORY POSITION

The following procedures for combining the values of the response of individual modes and the response to the three independent spatial components of an earthquake in a seismic dynamic analysis of a nuclear power plant structure, system, or component are acceptable to the NRC staff:

1. COMBINATION OF VALUES OF THE RESPONSE OF INDIVIDUAL MODES

Acceptable methods for combining the in-phase and out-of-phase modal response components in the low, transition, and high-frequency regions of the spectrum are described below.

The following notation is used to describe various methods for modal response combination:

Sa_i	=	Spectral Acceleration for mode i
R_i	=	Response of mode i
α_i	=	In-phase response ratio for mode i
Rr_i	=	In-phase response component for mode i
Rp_i	=	Out-of-phase response component for mode i
Rr	=	Total in-phase response component from all modes
Rp	=	Total out-of-phase response component from all modes
Rt	=	Total combined response from all modes
C_{jk}	=	Modal response correlation coefficient between modes j and k.

1.1 Combination of Out-of-Phase Low Frequency Modal Response Components

For combination of the out-of-phase modal response components, Reference 1 examined the Square Root of the Sum of the Squares (SRSS), NRC Grouping, NRC Ten Percent, Rosenblueth's Double Sum Combination (DSC), the NRC DSC, and Der Kiureghian's Complete Quadratic Combination (CQC) methods. The methods discussed below are acceptable to the NRC staff subject to the noted limitations.

In generalized form, all the out-of-phase modal response combination methods can be represented by a single equation:

$$Rp = \left[\sum_{j=1}^{n} \sum_{k=1}^{n} C_{jk} Rp_j Rp_k \right]^{1/2} \tag{1}$$

The mode correlation coefficients C_{jk} are uniquely defined for each method.

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 the methods for combination of the out-of-phase response components are equivalent to SRSS if there are no "closely spaced" modes.

In this case,

C_{jk} = 1.0 for j = k

C_{jk} = 0.0 for j ≠ k

and Equation 1 reduces to:

$$Rp = \left[\sum_{i=1}^{n} Rp_i^2 \right]^{1/2} \qquad (2)$$

Two consecutive modes are defined as closely spaced if their frequencies differ from each other by a certain percentage or less of the lower frequency. The percentage is a function of damping as follows:

10% at low damping ratios (≤2%).

5 times the damping ratio for higher damping ratios (e.g., 25% for 5% damping; 50% for 10% damping).

1.1.2 Rosenblueth's Double Sum Combination (DSC)

Rosenblueth (Ref. 6) provided the first significant mathematical approach to 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 coefficients C_{jk} as a function of the modal circular frequencies (ω_j, ω_k), modal damping ratios (β_j, β_k), and the time duration of strong earthquake motion (t_D) was derived.

$$C_{jk} = \frac{1}{1 + \left\{ \frac{\omega'_j - \omega'_k}{\beta'_j \omega_j + \beta'_k \omega_k} \right\}^2} \qquad (3)$$

where $$\omega'_{()} = \omega'_{()} \left[1 - \beta_{()}^2 \right]^{1/2}$$

$$\beta'_{()} = \beta_{()} + \frac{2}{t_D \omega_{()}}$$

Appendix D to Reference 1 tabulates numerical values of C_{jk} for the DSC Method 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 1000 sec. produced similar values for C_{jk} regardless of frequency. The most significant result is that C_{jk} is highly dependent on the damping ratio; for 2%, 5%, and 10% damping, C_{jk} ≈ 0.2, 0.5 and 0.8 respectively, at a frequency ratio of 0.9 (modal frequencies within 10%).

1.1.3 Der Kiureghian's Complete Quadratic Combination (CQC)

Der Kiureghian (Ref. 7) presents a methodology similar to Rosenblueth's Double Sum Combination for evaluation of modal correlation for seismic response spectrum analysis. It is also based on application of random vibration theory, but utilizes an infinite duration of white noise to represent seismic loading. The following formula for calculation of the coefficients C_{jk} as a function of modal circular frequencies and modal damping ratios was derived:

$$C_{jk} = \frac{8(\beta_j \beta_k \omega_j \omega_k)^{1/2} * (\beta_j \omega_j + \beta_k \omega_k) * \omega_j \omega_k}{(\omega_j^2 - \omega_k^2)^2 + 4\beta_j \beta_k \omega_j \omega_k (\omega_j^2 + \omega_k^2) + 4(\beta_j^2 + \beta_k^2)\omega_j^2 \omega_k^2} \quad (4)$$

While the form of Equation 4 differs significantly from Equation 3, the two equations produce equivalent results if t_D is assumed very large in Equation 3. This is shown in Appendix D to Reference 1, where C_{jk} is tabulated for DSC with t_D = 1000 sec. and for CQC.

1.2 Separation of Transition Frequency Modal Responses into Out-of-Phase Components and In-Phase Components

For separation of out-of-phase and in-phase components for the amplified modes, the methods of Lindley-Yow and Gupta (Refs. 8, 9) are acceptable with an exception that the Lindley-Yow method is not suitable for analysis of systems with significant low-frequency response ($f < f_{\text{spectral peak}}$).

For separation of the in-phase and out-of-phase modal response components, the methods proposed by Lindley-Yow, Hadjian and Gupta were examined in Ref. 1. The Lindley-Yow and Gupta methods were found acceptable by the staff, subject to the limitations discussed in the following paragraphs.

1.2.1 Lindley-Yow Method

In its most general form, the Lindley-Yow method (Ref. 8) may be defined by the following equations:

$$\alpha = ZPA / Sa_j \qquad 0 \le \alpha_i \le 1.0 \quad (5)$$

$$Rr_i = R_i * \alpha_i \quad (6)$$

$$Rp_i = R_i * \sqrt{1 - \alpha_i^2} \quad (7)$$

$$Rr = \sum_{i=1}^{n} Rr_i \quad (8)$$

$$Rr = \left[\sum_{j=1}^{n} \sum_{k=1}^{n} C_{jk} Rp_j Rp_k \right]^{1/2} \quad (9)$$

$$R_t = \sqrt{Rr^2 + Rp^2} \qquad (10)$$

where each C_{jk} is defined by one of the methods for combining the out-of-phase modal response components discussed previously (in Regulatory Position 1.1, Combination of Out-of-Phase Modal Response Components).

From these mathematical relationships, the following characteristics of the Lindley-Yow method are observed:

- $\alpha_i \rightarrow 1.0$ as $f_i \rightarrow f_{ZPA}$ (Sa_i = ZPA). Consequently, $f_{IP} = f_{ZPA}$ in the Lindley-Yow method.

- The in-phase component of modal response for every mode has an associated acceleration equal to the ZPA.

- The out-of-phase component of an individual peak modal response has an associated modified spectral acceleration given by

$$\overline{S}a_i = \left[Sa_i^2 - ZPA^2\right]^{1/2} \qquad (11)$$

- $R_i = (Rp_i^2 + Rr_i^2)^{1/2}$; which is based on the premise that the in-phase and out-of-phase response components of an individual peak modal response are uncorrelated and, therefore, can be combined by SRSS.

- All in-phase modal response components (Rr_i) are summed algebraically to obtain Rr.

- All out-of-phase modal response components (Rp_i) are combined by a suitable method discussed in Regulatory Position 1.1, Combination of Out-of-Phase Modal Response Components, to obtain Rp.

- The total response, Rt, is obtained by SRSS combination of Rr and Rp; i.e., Rr and Rp are uncorrelated.

- α_i attains its minimum value at $f_i = f_{SP}$, but increases for $f_i < f_{SP}$ until it attains a value of 1.0 when Sa_i = ZPA in the low frequency region of the spectrum. Values of $\alpha_i > 1.0$ have no meaning because $(1 - \alpha_i^2)^{1/2}$ becomes imaginary.

An obvious limitation of the Lindley-Yow method is in the low frequency range ($f < f_{SP}$) of the response spectrum. There is no physical basis for assuming that low-frequency modal responses become increasingly in phase with the input acceleration time history, which is an outcome if the Lindley-Yow method is applied to low-frequency modal responses. Modal responses in the low-frequency range are generally out of phase with the input acceleration time history. Therefore, the Lindley-Yow method is applicable to structural systems that do not have significant modal responses with $f_i < f_{SP}$. Lindley and Yow (Ref. 8) do not address this limitation. For the sample problems presented in Reference 8, the lowest system frequency is greater than f_{SP} of the applied response spectrum. Therefore, the results reported in Reference 8 are not affected by this limitation. Circumventing this limitation in the Lindley-Yow method is straightforward; it should be applied only to those modes with $f_i \geq f_{SP}$ and with $\alpha_i = 0$ for $f_i < f_{SP}$.

An independent evaluation of the Lindley-Yow method and its limitation is included as Appendix G to Reference 1.

For a structural system with fundamental frequency $\geq f_{SP}$, the Lindley-Yow method lends itself to a relatively straightforward physical interpretation. In the limit, if all modes are retained in the solution, the total mass participation is unity. Applying the Lindley-Yow method is equivalent to performing a static analysis of the system loaded by total mass times the ZPA, and performing the response spectrum analysis for amplified modes $f < f_{ZPA}$ using modified spectral accelerations, $\overline{S}a_i$ given by Equation 11. The total dynamic response is then obtained by SRSS combination.

The Lindley-Yow method automatically provides for algebraic combination of modal responses above f_{ZPA} because $\alpha_i = 1.0$, $Rp_i = 0$, and $Rr_i = R_i$. However, to completely account for the modal response above f_{ZPA}, all system modes of vibration need to be included in the analysis. This contribution is most accurately and efficiently calculated by use of the missing mass method discussed in Regulatory Position 1.3, Contribution of High-Frequency Modes. Therefore, while in theory the Lindley-Yow method includes the in-phase contribution from modes above f_{ZPA}, its practical application is for modal responses below f_{ZPA}, coupled with the missing mass method for modal contributions above f_{ZPA}. It is noted that the combination of the Lindley-Yow and the missing mass approach will produce identical results for any modal analysis cutoff frequency $\geq f_{ZPA}$.

1.2.2 Gupta Method

The Gupta Method (Ref. 9) is identical in form to the Lindley-Yow method with the one very significant difference being the definition of α_i. Equations 6 through 10, for example, remain the same. In the Gupta method, α_i is an explicit function of frequency based on a semi-empirical definition derived from numerical studies using actual ground motion records. A best-fit equation, which defines α_i as a continuous function of frequency, was developed from the results of the numerical studies.

Two spectrum-dependent frequencies (f_1, f_2) are first defined as follows:

$$f_1 = \frac{Sa_{max}}{2\pi Sv_{max}} \qquad (12)$$

where Sa_{max} and Sv_{max} are the maximum spectral acceleration and velocity, respectively.

$$f_2 = (f_1 + 2f_{ZPA})/3 \qquad (13)$$

Gupta's definition of α_i is given by:

$$\alpha_i = 0 \text{ for } f_i \leq f_1$$

$$\alpha_i = \frac{\ell_n(f_i / f_1)}{\ell_n(f_2 / f_1)} \text{ for } f_1 \leq f_i \leq f_2 \qquad (14)$$

$$\alpha_i = 1.0 \quad \text{for} \quad f_i \geq f_2$$

For a sharply peaked, in-structure response spectrum,

$$f_1 = f_{SP}$$

because Sv_{max} = Max (Sa_i / ω_i) = Sa_{max} / ω_{SP}

Substitution into Equation 12 yields

$$f_1 = \frac{\omega_{SP}}{2\pi} = f_{SP}$$

The corresponding definition of f_2 yields

$$f_2 = (f_{SP} + 2 f_{ZPA}) / 3$$

For a sharply peaked, in-structure response spectrum, the Gupta method has the following characteristics:

- For $f_i \leq f_{SP}$, $\alpha_i = 0$.
  Consequently, all modal responses with $f_i \leq f_{SP}$ are treated as out of phase. The limitation in the Lindley-Yow definition of α_i for $f_i \leq f_{SP}$ does not apply to Gupta's method.

- For $f_2 \leq f_i \leq f_{ZPA}$, $\alpha_i = 1.0$
  Consequently, all modal responses with $f_i \geq f_2$ are treated as in-phase. This is based on the fact that $f_{IP} = f_2$ in the Gupta method.

- Only modal responses with $f_{SP} < f_i < f_2$ are separated into out-of-phase and in-phase response components.

The potential limitations of the Gupta method lie in the semi-empirical basis for definition of α_i as a function of f_i. The range of applicability is difficult to assess without a comprehensive numerical study using ground and in-structure acceleration records, but in Reference 9, Gupta indicates that α_i can be numerically evaluated if the time history used to generate the response spectrum is known. It is implied, without stating, that numerical evaluation of α_i is more accurate than the semi-empirical definition of α_i given by Equation 14.

The overall structure of the Gupta method is superior to the Lindley-Yow method because there is no limitation for modal responses with $f_i < f_{SP}$. In addition, any value of $f_{IP} \leq f_{ZPA}$ can be accommodated by setting $f_2 = f_{IP}$, in lieu of Equation 13.

1.3 Contribution of High-Frequency Modes

For treatment of the high-frequency contribution, the Missing Mass method of Kennedy and the Static ZPA methods were examined in Reference 1. A draft revision (April 1995) of the American Society of Civil Engineers ASCE 4, "Seismic Analysis of

Safety-Related Nuclear Structures and Commentary on Standard for Seismic Analysis of Safety-Related Nuclear Structures" (Ref. 10) was also examined. The Missing Mass and the Static ZPA methods 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 mode superposition time-history analysis. In mode 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.

1.3.1 Missing Mass Method

The Missing Mass method is a convenient, computationally efficient and accurate method to

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) and

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 represented in the modes with frequencies below f_{ZPA}. The system response to the missing mass is calculated by performing a static analysis for applied loads equal to the missing mass multiplied by the spectrum ZPA. This method is mathematically rigorous and is considered the only acceptable method to account for high-frequency modal contributions ($f \geq f_{ZPA}$) and mass apportioned to system support points.

Kennedy (Ref. 11) documented this method and recommended that it be included in regulatory guidance. The 1989 revision to Section 3.7.2, “Seismic Analysis,” of the Standard Review Plan (SRP), NUREG-0800 (Ref. 12), incorporated Kennedy’s recommendation as Appendix A. The mathematical details are presented in both References 9 and 10. The mathematical formulation is included as Appendix I to Reference 1.

The guideline provided in References 11 and 12, 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 generate the missing mass loading. 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. 9). 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.

1.3.2 Static ZPA Method

The use of the Static ZPA Method is acceptable. Model discretization should be sufficient to accurately represent the distributed mass.

The Lindley-Yow Method (Ref. 8) defines the acceleration of the in-phase response component of all modes to be the ZPA of the response spectrum. The algebraic summation of the in-phase response components for all modes (Rr) 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 Rr 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 out-of phase response component (Rp) is calculated in accordance with the Lindley-Yow method.

Appendix C of Reference 1 provides insights into means of ensuring that the models used for these calculations produce satisfactory results. Guidelines for ensuring that the model discretization is sufficient to accurately represent the distributed mass are also provided there.

1.4 Complete Solution for Response Spectrum Analysis

Two methods are acceptable for obtaining the complete (in-phase and out-of phase) response spectrum analysis solution in each of the three orthogonal component motions, (two horizontal and one vertical) of a prescribed design earthquake. The coefficients C_{jk} in each method are determined by one of the out-of-phase combination methods (see Regulatory Position 1.1, Combination of Out-of-Phase Low-Frequency Modal Response Components).

The Lindley-Yow Method is not suitable for analysis of systems with significant low-frequency response ($f<f_{spectral\ peak}$); see Regulatory Position 1.2.

The contribution of high-frequency modes ($f \geq f_{ZPA}$) must be included in all response spectrum analyses.

The coefficients C_{jk} are defined by one of the out-of-phase combination methods (see Regulatory Position 1.2, Separation of Transition Range Modal Responses into Out-of-Phase Components and In-Phase Components).

1.4.1 Combination Method A

Combination Method A introduces the concept of in-phase and out-of-phase modal response components for the amplified modes ($f < f_{ZPA}$). This method is designated as Method 2 in Ref 1. Mathematically, the complete solution is represented by:

$$Rp_i = R_i \ * \ (1-\alpha_i^2)^{1/2}$$

$$Rr_i = R_i \ * \ \alpha_i$$

$$Rp = \left[\sum_{j=1}^{n} \sum_{k=1}^{n} C_{jk} Rp_j Rp_k \right]^{1/2} \qquad \text{n = number of modes below } f_{ZPA} \qquad (15)$$

$$Rr = \sum_{i=1}^{n} Rr_i \ + \ R_{\text{missing mass}}$$

$$Rt = \sqrt{Rp^2 + Rr^2}$$

Combination Method A is equally applicable to both the Lindley-Yow and the Gupta methods (Regulatory Position 1.2, Separation of Transition Range Modal Responses into Out-of-Phase Components and In-Phase Components). Only the definition of α_i changes.

1.4.2 Combination Method B

Combination Method B is a variation of the above, which uses the Static ZPA method to calculate Rr. This method is designated as Method 3 in Reference 1. Mathematically, the complete solution is represented by

$$Rp_i = R_i \ * \ (1-\alpha_i^2)^{1/2}$$

$$Rp = \left[\sum_{j=1}^{n} \sum_{k=1}^{n} C_{jk} Rp_j Rp_k \right]^{1/2} \qquad \text{n = number of modes below } f_{ZPA} \qquad (16)$$

$$Rr = R_{\text{static ZPA}}$$

$$Rt = \sqrt{Rp^2 + Rr^2}$$

Combination Method B is compatible only with the Lindley-Yow method, because calculation of Rr by the Static ZPA Method is based on the Lindley-Yow definition for α_i, using Equation 5.

2. COMBINATION OF EFFECTS CAUSED BY THREE SPATIAL COMPONENTS OF AN EARTHQUAKE

The term Rt in Equations 15 and 16 provides the total combined response in one of three orthogonal component motions (two horizontal and one vertical) of a prescribed design earthquake. However, the design of a Category 1 structure, system, or component should be based on the combined response from all three orthogonal component motions. Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants" (Ref. 13), amplifies this.

There are two methods for seismic analysis: response spectrum analysis and time-history analysis.

Depending on which basic method is used in the seismic analysis, i.e., response spectra or time history method, the two approaches in Regulatory Positions 2.1 and 2.2 are considered acceptable for the combination of three-dimensional earthquake effects.

2.1 Response Spectra Method

When the response spectra method is adopted for seismic analysis of uncorrelated seismic ground motions, the representative maximum values of the structural responses to each of the three components of earthquake motion should be combined by taking the SRSS of the maximum representative values of the codirectional responses caused by each of the three components of earthquake motion at a particular point of the structure or of the mathematical model. As an alternative, the 100-40-40 method of combination (Equation 17) 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 codirectional responses caused by each of the three components of earthquake at a particular point of the structure or of the mathematical model, such that

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

2. The maximum seismic response, Rmax, that is due to simultaneous earthquake loading in three directions is given by

$$Rmax = \pm(1.0 *|R_1| +0.4 *|R_2| + 0.4 *|R_3|) \qquad (17)$$

2.2 Time-History Analysis Method

For the time-history analysis when each of the three spatial components are calculated independently, Chu, Amin, and Singh (Ref. 4) concluded that the representative maximum value of a particular response of interest for design (e.g., stress, strain, moment, shear or displacement) of a given element of a structure, system, or component subjected to the simultaneous action of the three components of the earthquake can be satisfactorily obtained by taking the square root of the sum of the squares (SRSS) of the maximum values of the spectrum response from the time-history dynamic analysis for each of the three components calculated independently. Consistent with the use of the SRSS method for the response spectra analysis, the acceptability of the SRSS method is based on the assumption of uncorrelated seismic ground motions.

In addition to the SRSS method for combining the spatial components from a time-history analysis, a time-step method can also be used when the three spatial components are calculated simultaneously. In this method, the maximum value of a particular response of interest for design of a given element can be obtained through a step-by-step method. The time-history responses from each of the three components of the earthquake motions can be obtained and then combined algebraically at each time step or the response at each time step can be calculated directly owing to the simultaneous action of the three components. The maximum response is determined by scanning the combined time-history solution. When this method is used, the earthquake motions specified in the three different directions should be statistically independent. For a discussion of statistical independence, see Reference 14.

When the time-history analysis method is employed for seismic analyses, two types of analyses are generally performed depending on the complexity of the problem:

2.2.1 When the maximum response that is due to each of the three components of the earthquake motion are calculated separately, the method for combining the three-dimensional effects is identical to that using the SRSS method described above except that the maximum responses are calculated using the time-history method instead of the response spectrum method.

2.2.2 When the time-history responses from each of the three components of the earthquake motion are calculated by the step-by-step method and combined algebraically at each time step, the maximum response can be obtained from the combined time solution.
When this method is used, the earthquake motions specified in the three different directions should be statistically independent. For a discussion of statistical independence, see Reference 14.

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 the alternative acceptable methods that were used for analyzing the structures, systems, or components covered by that section.

D. IMPLEMENTATION

The purpose of this section is to provide information to licensees and applicants regarding the NRC staff's plans for using this regulatory guide.

This proposed revision has been released to encourage public participation in its development. Except in those cases in which the applicant or licensee proposes an acceptable alternative method for complying with specified portions of the NRC's regulations, the method to be described in the active guide reflecting public comments will be used in the evaluation of submittals that involve combining modal responses and spatial components in seismic response analysis.

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[1] Copies are available at current rates from the U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20402-9328 (telephone (202)512-1800); or from the National Technical Information Service by writing NTIS at 5285 Port Royal Road, Springfield, VA 22161; (<http://www.ntis.gov/ordernow>; telephone (703)487-4650. Copies are available for inspection or copying for a fee from the NRC Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR's mailing address is USNRC PDR, Washington, DC 20555; telephone (301)415-4737 or (800)397-4209; fax (301)415-3548; email is PDR@NRC.GOV.

12. “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants,” NUREG-0800, Section 3.7.2, “Seismic System Analysis,” Revision 2, August 1989.[1]

13. “Design Response Spectra for Seismic Design of Nuclear Power Plants,” Regulatory Guide 1.60, Revision 1, USNRC, December 1973.[2]

14. C. Chen, "Definition of Statistically Independent Time Histories," *Journal of the Structural Division*, ASCE, February 1975.

[2] Single copies of regulatory guides, both active and draft, and draft NUREG documents may be obtained free of charge by writing the Reproduction and Distribution Services Section, OCIO, USNRC, Washington, DC 20555-0001, or by fax to (301)415-2289, or by email to <DISTRIBUTION@NRC.GOV>. Active guides may also be purchased from the National Technical Information Service on a standing order basis. Details on this service may be obtained by writing NTIS, 5285 Port Royal Road, Springfield, VA 22161; telephone (703)487-4650; online <http://www.ntis.gov/ordernow>. Copies of active and draft guides are available for inspection or copying for a fee from the NRC Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR’s mailing address is USNRC PDR, Washington, DC 20555; telephone (301)415-4737 or (800)397-4209; fax (301)415-3548; email <PDR@NRC.GOV>.

REGULATORY ANALYSIS

1. STATEMENT OF THE PROBLEM

Revision 1 of Regulatory Guide 1.92, “Combining Modal Responses And Spatial Components in Seismic Response Analysis,” was issued in February 1976 to describe acceptable methods for complying with the NRC’s regulations in the design and evaluation of nuclear power plant structures, systems, and components important to safety.

Since the issuance of Revision 1 of Regulatory Guide 1.92, there have been advances in technology related to methods of estimating the forces applied to structures, systems, and components during an earthquake. In addition, while use of the SRSS method continues to be acceptable, it does not preserve the mathematical sign of the direction of the forces.

2. OBJECTIVES

The objective of the regulatory action is to update NRC guidance on the design and evaluation of structures, systems, and components subjected to earthquake forces and to make use of improvements in technology resulting, in part, from NRC-supported research activities.

3. ALTERNATIVES AND CONSEQUENCES OF PROPOSED ACTION

3.1 Alternative 1 - Do Not Revise Regulatory Guide 1.92

Under this alternative, Regulatory Guide 1.92 would not be revised and licensees would continue to rely on the current version of Regulatory Guide 1.92 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

The staff has identified the following consequences associated with adopting Alternative 2.

3.2.1. Licensees would be free to use the latest technology available, with consequent improvements in the design and evaluation of structures, systems, and components.

3.2.2. Regulatory efficiency would be improved by reducing uncertainty as to what is acceptable and by encouraging consistency in the design and evaluation of structures, systems, and components. 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.

3.2.3. An updated Regulatory Guide 1.92 would result in cost savings to both the NRC and industry. From the NRC's perspective, relative to the baseline, NRC will incur one-time incremental costs to issue the regulatory guide. However, the NRC should also realize cost savings associated with the review of licensee submittals. In the staff's view, the continual and on-going cost savings associated with these reviews should more than offset this one-time cost.

On balance, it is expected that industry would realize a net savings, as their one-time incremental cost to review and comment on a revision of a regulatory guide would be more than compensated for by the efficiencies (e.g., elimination of unnecessary conservatism, reduced follow-up questions and revisions) associated with each licensee submission.

4. CONCLUSION

Based on this regulatory analysis, it is recommended that the NRC 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, and it will result in an improved process for the design and evaluation of safety-related structures, systems, and components. Furthermore, the staff sees no adverse effects associated with revising Regulatory Guide 1.92.

BACKFIT ANALYSIS

The regulatory guide 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 rules or a regulatory staff position interpreting the Commission 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 systems, structures, 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 the orders of the Commission as described in 10 CFR 50.109(a)(7). This regulatory guide provides licensees and applicants an opportunity to use state-of-the-art methods that are available in one document.