DIRECT GENERATION OF SEISMIC RESPONSE SPECTRA

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ABSTRACT

This paper presents a methodology by which seismic in-structure response spectra may be generated directly from either ground or floor excitation spectra. The method is based upon stochastic concepts and utilizes the modal superposition solution. The philosophy of the method is based upon the notion that the evaluation of 'peak' response in uncertain excitation environments is only meaningful in a probabilistic sense. This interpretation of response spectra facilitates the generation of in-structure spectra for any non-exceedance probability (NEP).

The method is validated by comparisons with a set of deterministic time-history analyses with three example models : an eleven-story building model, a containment structure stick model. and a floor mounted control panel, subjected to ten input spectrum compatible acceleration time-histories. A significant finding resulting from these examples is that the time-history method portrayed substantial variation in the resulting in-structure spectra, and therefore is unreliable for the generation of spectra. It is shown that the average of the time-history generated spectra can be estimated by the direct generation procedure. and reliable spectra may be generated for .85 NEP levels.

Also included in the paper, is a review of the stochastic methods proposed by Singh [1], Der Kiureghian et al. [2] and the Fourier transform method proposed by Scanlan et al. [3].

1 INTRODUCTION

The seismic qualification of equipment in nuclear power plants is typically performed by means of response spectra analyses. Due to the inherent uncertainty in earthquake ground motions. a realistic assessment of equipment response is a rather difficult task. The difficulty lies largely in the quantitative characterization of the ground motion itself.

Currently, seismic input motions are most conveniently characterized by response spectra (RS). For nuclear power plant design, site design earthquakes (OBE and SSE) are represented by response spectra and may be either of a standard shape (e.g. RG 1.60) or site specific. The ground response spectra can generally be used directly for the analysis and design of primary systems. However, generation of floor and component response spectra, which is required for the qualification of equipment and piping systems, is not a direct process.

The conventional approach to the generation of in-structure spectra involves a time-history analysis of the primary structure. An acceleration time-history record (compatible with the ground spectrum) and a dynamic model of the primary structure are used to generate acceleration time-histories at desired locations (typically the floor levels) within the primary structure. From these, floor response spectra are generated for use in equipment qualification. A similar procedure, using floor spectra as a starting point, is used to generate spectra within these sub-systems. These are used to qualify sub-systems such as control panel components, valves, etc. This process is only valid if equipment-structure interaction is negligible. Generally the relatively light weight of equipment produces negligible interaction with the overall response of the primary system, and thus sub-systems can be analyzed independently from the primary systems to which they are attached.

This deterministic procedure is analytically correct but unreliable from a probabilistic standpoint in view of the following : 1) clearly, seismic occurrences and characteristics are non-deterministic - 2) a large number of time-histories with their response spectra compatible to the input spectrum can produce large variations in the response of the equipment. This is undesirable since, if a single time history analysis is performed, the accuracy of the results from either a conservative or non-conservative basis cannot be assured. To overcome this problem via deterministic time-history analyses, a large number of time-history analyses are required and their mean or mean-plus-one-standard-deviation must be calculated.

As an alternative to the deterministic time-history approach, this paper presents a direct spectra generation methodology based upon a stochastic analysis formulation. The idea of stochastic direct spectra generation is not new - several such methods have been proposed in recent years. While some of these approaches have shown promise in being able to generate floor spectra, none has yet been applied to the generation of spectra in secondary systems (i.e. floor-to-equipment). This distinction is made because earthquake ground motion exhibits wide-band process characteristics while floor motion portrays narrow-band characteristics strongly reflecting the filtering effect of the primary structural system. The desirability of using the direct generation method of computing response spectra has been recommended in Ref.[7] to overcome the problems associated with the single time-history analysis method.

The method proposed herein evolved in the pursuit of an evaluation study, presented in Section 4, of direct spectra generation techniques proposed by Singh [1], Der Kiureghian et al. [2], and Scanlan et al. [3]. The motivation that prompted such a development arose out of the inapplicability of the stochastic methods [1][2] to narrow-band excitations. The new approach is shown to produce excellent results both for primary and secondary systems. The enhancement results from the use of the excitation power spectral density function (PSDF) explicitly, which the other methods avoid. The PSDF is generated utilizing the input response spectrum as information partially characterizing potential ground motions at a particular site.

2 FORMULATION

The method presented herein is a stochastic analysis methodology. It is illustrated schematically in Fig. 1, which depicts a linear n-dof primary structural system (possessing classical modes) subjected to base excitation. As shown, the possibility of equipment-structure interaction is also included as an optional consideration. Der Kiureghian et al. [2] have developed an ingenious perturbation technique which facilitates the response evaluation of the coupled system without explicit modeling of the secondary component in the combined model. This is done by augmenting the primary system with an extra degree-of-freedom (n+1) through a perturbation scheme. The implication here is that one is able to evaluate secondary 1-dof system response directly through a set of spectra parametrized by equipment mass. This could result in significant reduction of secondary system support design loads.

The proposed methodology essentially involves stochastic response evaluation through the PSDF characterization of excitation and response, via modal superposition. The central issue here is the proper interpretation of the relation between the RS and the PSDF. It must be emphasised that this is the feature that facilitates the analysis of response due to narrow-band excitation.

In evaluating structural response due to random excitation, such as earthquake ground motion, the notion of 'peak' response (such as response spectra) is only meaningful in a probabilistic sense - i.e. the issue becomes one of assessing structural performance such as barrier exceedance, involving a discrete probability. Mathematically, the famous 'first-passage problem' lends itself as a very useful model for the quantitative treatment of such problems. Within the stochastic context then, the link between the RS and the PSDF may be established by a first-passage problem interpretation.

Restricting the discussion to stationary excitation initially, spectral response may be interpreted as the threshold level 'a' with which a specific non-exceedance probability (NEP) is associated. On the basis of simulation and theoretical studies, for linear systems subjected to suddenly applied steady-state stationary Gaussian excitation of finite duration, Vanmarcke [4] and Crandall et al [5] suggest an exponential representation of this NEP, through the following cumulative probability distribution function:

$$P(t) = A \exp(-\alpha t) \tag{1}$$

applicable over the excitation interval (0,t). The parameters A and α are functions of the barrier level 'a', associated with the first-passage model, and the spectral moments of a 1-dof oscillator response process PSDF, G_X - due to the base motion PSDF, G_E - which are given by :

$$\lambda_m = \int_0^\infty \omega^m G_X(\omega)\, d\omega \; ; \qquad m = 0,1,2 \tag{2}$$

Thus, identifying the response spectrum ordinate, S_r, with the barrier level 'a', and the time interval (0,t) with the strong motion duration, s, of the postulated seismic excitation, Eq. (1) yields :

$$S_r = p\sigma_X \; ; \qquad \sigma_X^2 = \int_0^\infty G_E(\omega)\; |H(\omega;\omega_o,\xi_o)|^2 d\omega \qquad (3)$$

where : the peak factor $p = p(\lambda_{0,1,2}, s, NEP)$, $NEP = P(s)$, and H is the 1-dof oscillator complex frequency response function.

The inversion of Eq. (3) yields the base motion PSDF sought. Since the peak factor is a function of the spectral moments, the inversion process is most conveniently performed via iterative schemes. This interpretation of the response spectrum has resulted in the successful generation of narrow-band (Fig. 6) as well as wide band PSDF's.

It must be emphasised, at this point, that the PSDF of a given process is unique and provides a second order (in terms of cumulant functions) probabilistic description of the stochastic process (in fact a complete description for a weakly stationary Gaussian process) - while a discrete probability of non-exceedance is associated with the RS. This aspect of the RS-PSDF relationship suggests the requirement of A PRIORI knowledge of the NEP associated with a given input spectrum (ground or floor). In fact, the RG 1.60 spectra have been constructed statistically per the MSD (mean-plus-one-standard-deviation) procedure utilizing an extensive data base of recorded seismic time-histories (see Ref. [6]) - hence an 'NEP-parametrization'. Ref.[7] does actually recommend the use of probabilistically generated in-structure spectra corresponding to a .84 NEP, in lieu of deterministic spectra. (Note that a .84 NEP corresponds to an MSD procedure for a Gaussian distribution).

Having established the excitation PSDF, the response PSDF associated with any degree-of-freedom 'k' follows readily from :

$$G_{kx}(\omega) = \Sigma_i \Sigma_j\; \Psi_{ix}(k)\Psi_{jx}(k) G_E(\omega)\; H_i(\omega;\omega_i,\xi_i)\bar{H}_j(\omega;\omega_j,\xi_j) \qquad (4)$$

where $\Psi_{ix}(k)$ is the effective i-th modal participation factor associated with dof 'k' due to excitation in x-direction, $H_i(\omega;\omega_i,\xi_i)$ is the complex frequency response function of mode i - where ω_i, ξ_i are the modal frequency and damping respectively, and $\bar{H}$ denotes the complex conjugate of H.

The mathematical treatment so far has been within the framework of the stationarity assumption. Seismic processes being transient events, are non-stationary in character thus neccessitating the consideration of this effect into the formulation. In the development presented above, non-stationarity is actually partially reflected through the RS-PSDF relationship by virtue of the connection between excitation response spectra and actual seismic records. The analytical incorporation of non-stationarity effects, into the above stationary formulation, may be accomplished through the augmentation of spectral damping as suggested by Rosenblueth and Elurdoy [9] and Vanmarcke [5].

Thus, response spectra parametrized by NEP, damping, and, if desired, equipment mass may be obtained from the inverse process applied in deriving the excitation PSDF.

3 EVALUATION

An evaluation of the proposed methodology was performed by comparing the directly generated spectra with those generated from ten deterministic time-history analyses. Three dynamically different structural types were utilized for this evaluation, each of which was subjected to an ensemble of ten acceleration time-histories that all closely enveloped either the floor or ground response spectra.

The structures analyzed were as follows : 1) an eleven-story reinforced concrete building model (see Ref.[8]) of 528 degrees-of-freedom and 10 modes in the 1-7 Hz frequency range. 2) a containment type structure stick model of 12 degrees-of-freedom and 6 modes in the 8-60 Hz frequency range and 3) a floor mounted control panel structural model of 1623 degrees-of-freedom and 25 modes in the 18-134 Hz frequency range.

For the analyses of the structural models (building and containment), the input ground response spectrum is shown in Fig. 2. For the deterministic analyses, ten acceleration time-histories were generated that were compatible with the ground response spectrum. An example of the typical degree of compatibility is shown in Fig. 2. For each structural model, response spectra at the top slab locations were generated corresponding to each of the ten time-history inputs. The resulting set of floor response spectra exhibited significant variability in the peak amplitudes. An example of the variability of the set for the eleven-story building model is shown in Fig. 3, clearly illustrating the limitations of the time-history results. For the purposes of comparison with the direct generation method the arithmetic-mean response spectra of each set of ten floor spectra were obtained. These are shown in Figs. 4 and 5 together with the stochastic median (50% NEP) response spectra obtained by the direct method. The close agreement between these "average" response spectra obtained from both methods is indicative of the reliability of the direct generation method. Another major advantage of the direct generation method proposed herein is that whatever level of NEP spectra is required can be generated. An example of this, for the eleven-story building, is shown in Fig. 4.

The procedure utilized to evaluate the method for the floor mounted control panel model is identical to the previous examples except for the input. In this case, the 85% NEP stochastic spectrum associated with the top slab of the containment model response was utilized as the input. The ten time-histories required for the deterministic analyses were generated such that they closely enveloped the floor spectrum. The PSDF for the direct generation method in this case is certainly narrow-band as shown in Fig. 6. Response spectra at one point or component location in the control panel were determined by both methods. As in the previous example, the time history response spectra at the component location exhibits significant variability in the peak amplitudes as shown in Fig. 7 (recall that for this example the panel frequencies range from 18-134 Hz). A comparison of the 50% NEP (median) and 90% NEP spectra, generated by the direct method, with the time-history mean spectrum is shown in Fig. 8, which, with the variability of the time-history spectra shown in Fig. 7 clearly demonstrate the predictive capability of the direct method.

4 COMPARISON WITH ALTERNATE METHODS AND CONCLUSIONS

This section presents a review of the direct spectra generation methods proposed by Singh [1], Der Kiureghian et al. [2], and Scanlan and Sachs [3] and a comparison of their performance with the method proposed in this paper. The presentation comprises a brief statement about the concepts underlying each method, followed by comparisons with the results obtained in Section 3.

The method proposed by Singh is based upon a stochastic PSDF characterization of excitation and response - modal superposition is utilized as the solution technique. Spectral response is assumed to be proportional to the standard deviation of the associated spectral stochastic process (excitation and response) and the same proportionality constant is applied both at the excitation and response levels. This is essentially equivalent to a constant peak factor approach. Further, the assumption is made that the excitation PSDF is a wide-band smoothly varying function. Although the PSDF concept is used as theoretical background, its explicit determination is avoided through the implementation of the assumptions stated above. Thus, the formulation is only applicable to wide-band inputs and, because a constant peak factor is assumed, distributed or discrete probability does not enter the analysis.

The approach proposed by Der Kiureghian et al. is also developed on stochastic concepts utilizing PSDF characterization and modal superposition. An interactive primary structure-light equipment system is treated through a perturbation scheme which facilitates the response evaluation of single degree-of-freedom secondary systems directly without explicit modeling of the secondary system into the primary (see Fig. 1). This is accomplished through the augmentation of the primary system with an extra degree of freedom by means of a closed form perturbation scheme. The response spectrum is interpreted as the mean peak response of a 1-dof oscillator exposed to the stochastic process - which is assumed to be stationary Gaussian. A mean peak response is formulated through process statistics, such as spectral moments and peak factors, and modal combination utilizing the wide-band excitation assumption. As in Singh's method, the PSDF is utilized for theoretical purposes and avoided in the response determination. In addition, an expression for the standard deviation of the peak response process is developed, which facilitates the performance of MSD type of procedures, thereby providing the option of obtaining spectra with desired reliability levels. Thus spectra may be obtained directly, parametrized by equipment mass and reliability.

The Scanlan and Sachs method is based upon a Fourier transform technique. The central concept involves the correlation of the excitation response spectrum with the amplitudes of the randomly phased harmonic components which the compatible seismic record is assumed to be composed of. Although the excitation time history is alluded to in the theoretical development, it actually is not explicitly developed. The response is evaluated in the frequency domain through the transfer function characteristics of the structure which are reflected through its modal properties. The approach is somewhat pseudo-stochastic in that the random phase angles of the harmonic components are assumed to have a uniform probability distribution over the interval $(0,2\pi)$ and the assumption is made that spectral acceleration is proportional to the standard deviation of the acceleration response. There are no limitations as to the applicability of the method with respect to excitation characteristics.

To illustrate the performance of these methods for ground excitation applications, the eleven-story building example has been utilized - the spectra obtained from each method are shown in Fig. 9. For the floor excitation case the Scanlan and Sachs method (being the only applicable) is compared with the deterministic mean spectrum obtained from the ensemble responses for the floor mounted control panel model. These are shown in Fig. 10.

An analysis of Figs. 3,4,9 and 7,8,10 leads to the following observations : 1) regardless of the method, all spectra exhibit peaks at the dominant structral frequencies - 2) results due to Singh's formulation tends to underestimate, in general, as compared to the time-history mean spectrum and the other methods - 3) the mean peak response due to the Der Kiureghian et al. method is in close agreement with the time-history mean spectrum and also the method proposed herein (CES) - 4) the Scanlan and Sachs method produces a spectrum for the ground excitation example that seems to have an 'upper-bound' character whereas for the control panel case it portrays more of a 'mean' character.

It is clear from these observations that the spectra generated by the Singh and Scanlan and Sachs method cannot be conclusively identified as 'maximum', 'mean', 'median', or 'most probable'. However, the spectra that result from the method proposed herein and the Der Kiureghian formulation are identified with probability measure, by definition, and are shown to yield excellent results.

5 REFERENCES

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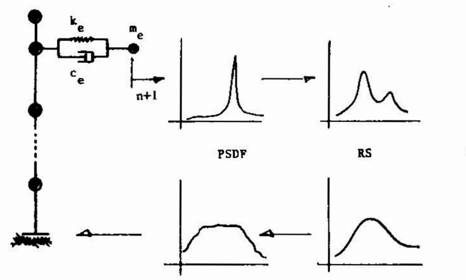

FIG. 1 - ANALYTICAL MODEL

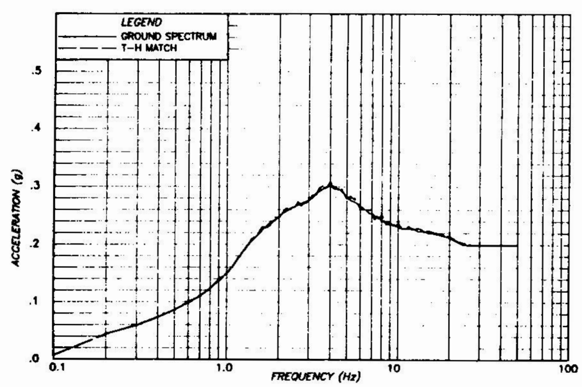

FIG. 2 - INPUT GROUND SPECTRUM

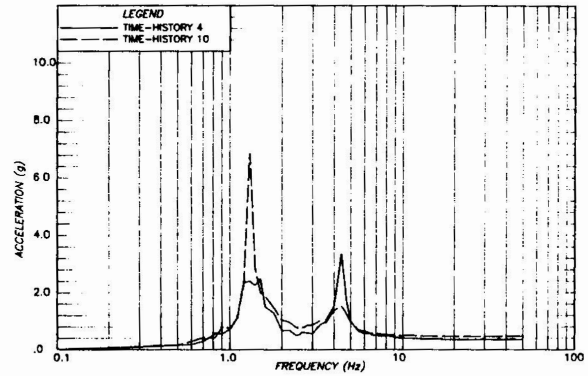

FIG. 3 - BUILDING MODEL : VARIABILITY OF T-H SPECTRA

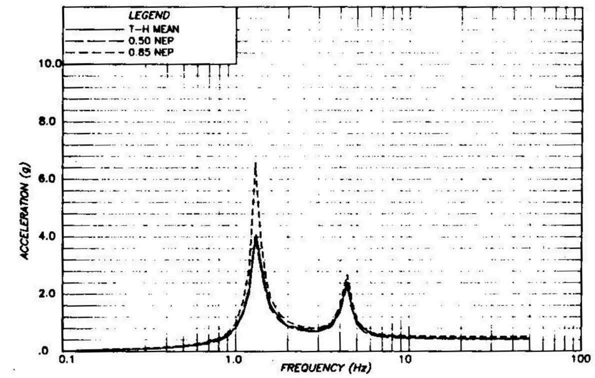

FIG. 4 - BUILDING MODEL : T-H MEAN AND VARIOUS NEP LEVELS

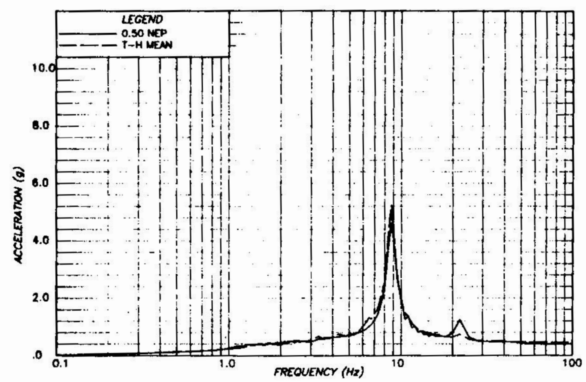

FIG. 5 - CONTAINMENT MODEL : T-H MEAN AND STOCHASTIC MEDIAN

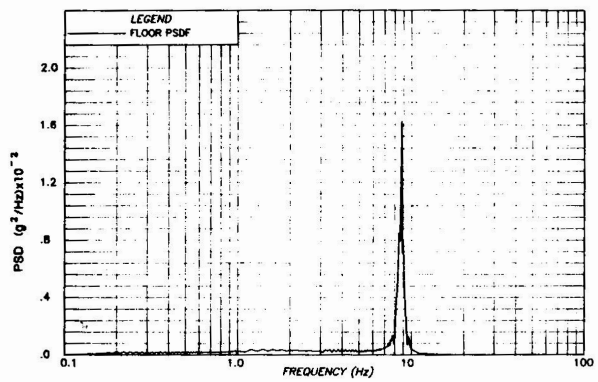

FIG. 6 - CONTROL PANEL MODEL : INPUT PSDF

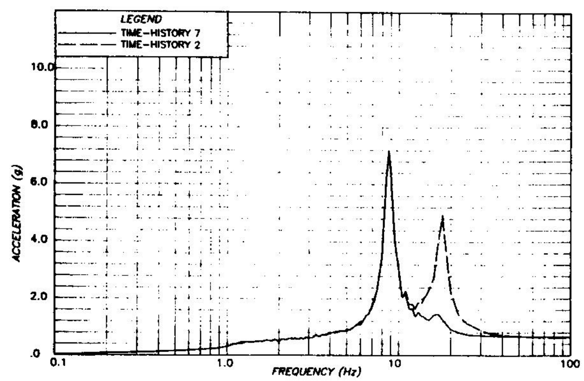

FIG. 7 - CONTROL PANEL MODEL : VARIABILITY OF T-H SPECTRA

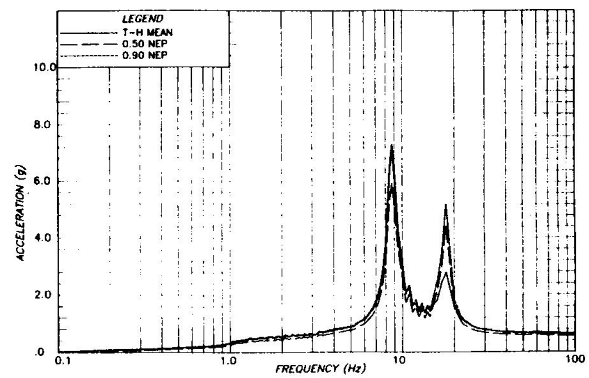

FIG. 8 - CONTROL PANEL MODEL : T-H MEAN AND VARIOUS NEP LEVELS

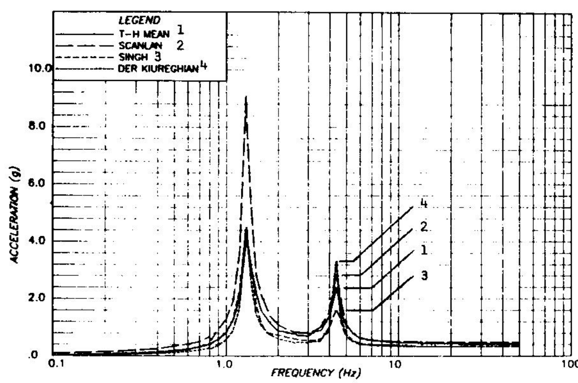

FIG. 9 - BUILDING MODEL : SINGH, DER KIUREGHIAN, & SCANLAN SPECTRA

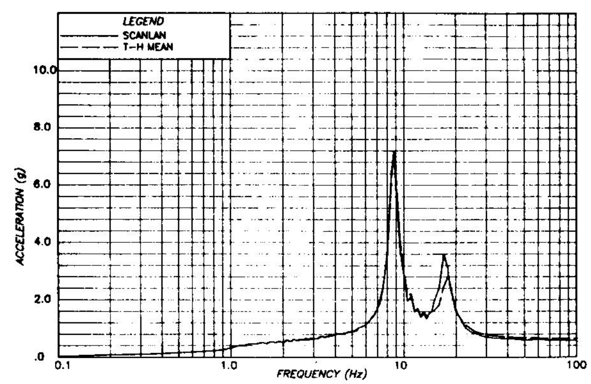

FIG. 10 - CONTROL PANEL MODEL : SCANLAN SPECTRUM AND T-H MEAN