CRITERIA FOR THE GENERATION OF SPECTRA
CONSISTENT TIME HISTORIES

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SUMMARY

Several methods are available to conduct seismic analysis for nuclear power plant systems and components. Among them, the response spectrum technique has been most widely adopted for linear type of modal analysis. However, for designs which consist of structural or material nonlinearities such as frequency dependent soil properties, the existence of gaps, single acting tie rods, and frictions between supports where the response has to be computed as a function of time, time history approach is the only viable method of analysis. Two examples of time history analysis are: 1) soil-structure interaction study and, 2) a coupled reactor coolant system and building analysis to either generate the floor response spectra or compute nonlinear system time history response.

The generation of a suitable time history input for the analysis has been discussed in the literature. Some general guidelines are available to insure that the time history input will be as conservative as the design response spectra. Very little has been reported as to the effect of the dynamic characteristics of the time history input upon the system response. In fact, the only available discussion in this respect concerns only with the statistical independent nature of the time history components.

There are several approaches currently being used by the nuclear industry to generate design time history input. None of these produce unique results. That is, given a design response spectrum, nearly unlimited number of synthesized time history motions can be constructed. The effects of these time history motions on the system response vary and they have not been properly evaluated.

For instance, some time histories may have high frequency content, higher than indicated by the real earthquake records. This may have adverse influence on the system response with high frequency impact or predominate high frequency modes. Other time histories may have unnecessarily long duration which makes a large and detailed analytical model uneconomical. The influence of the time history duration is primarily on the number of peak response stress cycles computed which can be either extrapolated from limited duration input or determined using other means. Rarely is the case that duration has to be kept long enough for the structure response to reach its peak. Consequently, input duration should be kept no longer than necessary to produce peak response to allow the use of more sophisticated model which enables the problem to be studied thoroughly. There are also time histories which have satisfied the generally accepted definition of statistical independent requirements, but possess statistical characteristics unlike those of the real earthquakes. Finally, some time histories may require smaller integration time steps than ordinarily used to insure that certain systems will have converge and stable solutions.

In this paper, numerical results for cases discussed above are presented. Criteria are also established which may be advantageously used to arrive at spectra consistent time histories which are conservative and more importantly, realistic.
1. INTRODUCTION

The use of response spectrum technique to qualify the structures, systems, and components in a nuclear facility was first recommended by a report prepared for the then US AEC in 1963 [1]. The design response spectrum was used for ground supported items such as concrete structures. Since then, the response spectrum technique has been extended to include system and components housed inside a structure by the development of floor (in-structure) response spectra applicable at the supports elevations.

Several methods have been proposed to generate the floor response spectra. One being the frequency response technique recommended by Biggs [2], and Kappur [3]. This technique requires that the modal response of the supporting structure (such as the concrete building) be considered purely sinusoidal. This is very conservative because the presence of building damping and the random nature of the earthquake motions. The other technique [4] which has been reported in the literature but has not gained large following in the industry uses spectral density functions. The results obtained using this technique by including the spectral density functions of real earthquakes can be more realistic than those obtained by the frequency response technique. The need to combine all significant structural modal responses via a root mean square or other argumental means, however, leads to the uncertainty that verification of the final results using other means may still be necessary. In addition to the above, there is the definite need of qualifying certain systems and components or even structures by a time history analysis. This may be in the form of soil-structure interaction study which accounts for the nonlinear soil behavior [5], or it may be in the form of a coupled building and reactor coolant system nonlinear time history analysis to generate floor response spectra or to conduct actual qualifications of the system [6]. The fact that nonlinearities exist in most of the support design, such as gaps, friction surfaces, and single acting tie rods, means that a time history analysis to account for the actual motion of the system and, therefore, a direct evaluation of the response behavior is most desirable.

The direct method of floor response spectra generation utilizes as input at the structural base the time history motion synthesized by ensuring that its response spectrum matches the design response spectra. The output time history at any structure node can be used directly as input for the analysis of systems and components, or it can be used to generate the floor response spectra. There is no assumption necessary in combining the structural modal response if normal mode analysis is used as in the case of spectral density function technique and the Fourier spectrum method.

There are two basic methods to generate the input time history motion which has the response spectra consistent with the design response spectra. One is to use an actual earthquake accelerogram by adding to or suppressing from the energy content of the time history [7, 8]. The second approach is to simulate the frequency content of the design response spectrum by starting from a spectral density function, a combination of sine waves with randomly selected phase angles, or other statistical or Fourier properties [9].

Some assurance has to be provided so that the time history input will have similar characteristics as an earthquake motion. Criteria have been suggested in the past to limit the correlation coefficients for the time history components to a very small value [10, 11].
There has been no discussion in the literature on producing a realistic time history input to satisfying the need of a sophisticated analysis for a complex system such as often encountered in a nuclear facility. The objective of this paper is to establish criteria on some of the most pertinent issues in the time history input generation so that dynamic analysis can be performed efficiently and realistically.

2. FREQUENCY CONTENT OF THE TIME HISTORY INPUT

The reactor coolant support system is most important to the safety function of a nuclear power plant. In the case of Westinghouse Pressurized Water Reactor, it consists of two to four loops each with a steam generator, a reactor coolant pump, and coolant pipes connecting to the reactor pressure vessel. The steam generator is typically supported horizontally at the upper portion by snubbers and at the bottom by columns and support frames. Gaps are provided wherever necessary to allow thermal expansion. For the reactor coolant pump, tie rods are provided, in addition to the support columns. These tie rods are single acting and, therefore, perform in a very nonlinear manner. As for the reactor pressure vessel, it is allowed to slide within the support shoes and free to have uplift motion within each shoe. The system has dynamic characteristics which cannot be easily predicted by linear analysis unless conservative assumptions are made.

The predominate modes of the system never exceed 33 Hz. Where impact occurs at the support gaps due to large motions, however, it may possess energy in natural frequencies as high as 50 Hz. This type of impact motions consist of short pulses which rarely present any significant design problems. When it is used to generate response spectra for the analysis of auxiliary pipings attached to the system, large response amplitude may occur at this high frequency. High frequency modes in the piping have small modal participation and low displacements. Therefore, the visual impact of its presence is probably greater than its contribution to the piping stresses. Nevertheless, it is desirable to either remove or reduce such high frequency motion from the system response. This can be accomplished by requiring that the input time history does not have frequency content higher than 33 Hz.

The design response spectra recommended in Regulatory Guide 1.60 converge to the maximum ground acceleration for all damping values at 33 Hz. This indicates that systems and components having natural frequencies greater than this value can be considered as rigid and sees only the maximum ground acceleration. In generating the spectrum consistent time history, the significance of the high frequency (higher than 33 Hz) has not been fully recognized to date. It has been a general practice to limit the time history response spectrum to be within a specified percentage of the design response spectrum, say 10%. The margin a: and above 33 Hz is usually liberally defined. This leads to possible frequency content which may excite structures and systems with natural frequencies higher than 33 Hz. For systems with support nonlinearities such as the reactor coolant loop support systems, this excitation further compounds the impact behavior which may produce undue concern to the design and qualification of the auxiliary piping. For this reason, it is recommended that all excess frequency content at and above 33 Hz be removed from the time history input.

When time history generated on a spectrum consistent basis is applied at the base mat, such as in the case of hard foundation sites, it is required by the standard in review plant [12] that the time history response spectra should envelope the corresponding design response
spectra for all damping values actually used in the analysis. It is not possible, however, to envelope spectra for all damping values without creating excessive conservatism for some. A remedy would be to reduce the number of spectra that need to be matched to the damping values of the structures, systems, or the combined structure and system models where the time history input is to be applied directly. Ramping values of subsystems attached to the structure or the system which are not included in the model need not be considered. Furthermore, only those damping values which are appropriate for the design basis, either OBE or SSE, associated with the time history should be considered only.

For the case where soil structure interaction is considered, the time history response spectra should match the design response spectra for the soil and structure damping values associated with the design condition.

3. DURATION OF THE TIME HISTORY

It has been observed in [13] that the earthquake duration effect on the response spectrum shape is small for periods shorter than 0.5 seconds, which is the period range significant for nuclear power plant structures, systems, and components.

Although long duration earthquakes tend to excite a much wider range of frequencies, this effect is actually being factored in the nuclear power plant design by using the smoothed, envelope type of design response spectra. The use of design response spectra is qualifying structures and components dictates that only maximum response amplitudes, be it displacements or stresses, are computed. The duration of ground motions, which has a strong influence in prolonging large amplitude structural response, is important only when fatigue life of the structures and components becomes a design factor. Such is rarely the case due to low probability of OBE occurrences and the limited maximum number of stress cycles and the relatively low stress levels permitted for each OBE. In any event, the maximum number of stress cycles is specified in the design.

The earthquakes used in the study which produces the recommended response spectra in Regulatory Guide 1.60 occurred almost exclusively in the California area originating along the CircumPacific Belt. These earthquakes are associated with moderate distances from the focus and occur only on firm ground. More importantly, they are extremely irregular and unlike those occurring on soft soil such as the Mexico City earthquakes of July 6, 1964, which last for only a moderate time. Maximum accelerations of these earthquakes generally occur in the first 10 seconds of strong shaking. For instance, the North-South component acceleration recorded at El-Centro, May 18, 1940, earthquake shows that the maximum horizontal ground acceleration of 0.33g occur at about 2 seconds after the instrument started recording.

In a response spectrum analysis using floor response spectra as input, duration of the artificial time histories does not come into the picture. Whereas, in the time history analysis, particularly when nonlinearity is present, long seismic inputs could make detailed analysis impractical, thereby limiting the size and accuracy of the mathematical model and the number of parametric studies of the model that can be performed. It is, therefore, of the utmost importance that duration of the artificial time history motions be made as short as practical.
On the other hand, duration of the artificial time histories should be sufficient to allow the structure enough time to achieve its maximum response. As an example, single degree-of-freedom system subjected to continuous sine wave motions will approach its maximum response asymptotically when enough cycles of sine waves have been applied. The number of cycles required is a function of both system frequency and the damping ratio.

As a generalization, therefore, the duration of the artificial time history motions should be as long as necessary for a single degree-of-freedom system to reach its maximum response (for a given damping), as required by the design response spectrum. As a typical example, it has been found that the initial 6 seconds of the 1940 El-Centro earthquake N5 component produces response spectra nearly identical to those generated by the whole record. The use of such short time history does not impair the analysis in anyway, as can be noted by the extensive use of a comparable 6.29 seconds record [13]. Furthermore, when required, this short duration record can be modified to include more shorter or longer periods of energy by using the method of Reference [8]. Within the frequency of interest for systems and components designed for nuclear power plants, e.g., greater than 2 Hz, the total number of sine wave cycles necessary to excite the system to its maximum response is about 6 for damping values of 5% critical or below. For other damping values usually used in a nuclear power plant design, it is generally less than 10. This means that the minimum duration has to be 3 seconds. However, to be reasonable, a 6 second duration should be used for the purpose of generating artificial time history motions as a minimum requirement.

4. PHASE RELATIONSHIP OF THE INPUT TIME HISTORY COMPONENTS

Current requirements of using all three components of the design response spectra in the design of a nuclear power plant [14] have increased the severity of the horizontal motion by as much as 41% from the old two components approach. Although actual figures could be smaller since maximum response from each horizontal component input rarely occurs at the same location of a system [15]. In a time history analysis, where the time phase relationship exists between the input components, the maximum response from each horizontal component input would neither occur at the same location nor at the same time. Variation in the time phase relationships could produce significantly different results in the structural response.

The limited publication to date on the time phase relationship has been to define the statistical independent nature of the real earthquake records [10]. Only cross-correlation coefficients at zero time delay have been studied. Cross-correlation coefficients at zero time delay cannot form a sound basis for determining completely the time phase relationship between the input components. It can be shown that by shifting one input component slightly along the time axis, the cross correlation coefficients at zero time delay for the shifted and the original components can be very small. Above the zero time delay, however, the correlation coefficients may achieve unity and fluctuate with large values.

Consequently, in order that the synthesized time histories will possess the dynamic characteristics of a real earthquake, it is necessary to compare the auto-correlation and cross-correlation coefficient functions for the component motions with a real earthquake records. This comparison should be carried out when the input time history components are generated by synthesizing an actual earthquake record. Since the synthesisization process tends to enrich frequency content of the time history above a real earthquake, a limited increase, such as 30%, should be allowed for the cross-correlation coefficients.
In the cases where the input time history components are generated by either stationary or non-stationary processes or other methods which do not use an actual earthquake record, comparison with a single earthquake motion cannot be made. Instead, it may be necessary to compare the cross-correlation coefficients with an ensemble of earthquake records.

5. INTEGRATION TIME STEP

The convergence of a solution, in any integration scheme, to a desired accuracy depends on the selection of an appropriate integration step size. Current industry practice is to use a value of 0.01 second. For systems and structures with low predominate natural frequencies, this value is appropriate. For system and components where higher frequency modes may be significant, this step size has been shown to produce non-convergent solutions. It is necessary, therefore, to select the integration step size based on the shortest natural period (or the longest natural frequency) of which the structural response is significant. For instance, in the Newmark-Beta integration scheme, a general guideline is to choose a step size of 1/20 to 1/30 of the shortest natural period of importance. For a complex system where nonlinearities exist, such as in the case where impact may present, a step size as small as 0.005 second could be necessary, unless a convergence study is conducted to ascertain the required value.

The response of a system or structure can be meaningful only if the input is accurate. In the case of the integration step size, to have the input time history generated and digitized at least equal to the value used in the analysis can further enhance the validity of the results. It is possible that the sharp but small vibration history traces neglected for ordinary analysis may have large importance in the instance of high frequency response.

Furthermore, it can be shown that if accuracy of the solution is important at high frequencies, then it is equally important to choose a small enough integration step size such that the spectrum consistent time history can be generated accurately at the higher frequencies.

6. CONCLUDING REMARKS

In order that the response of a nuclear facility to earthquake loads can be computed realistically and efficiently, the generation of spectrum consistent time history motion should take into consideration not only the nature of the earthquake motions but also the dynamic characteristics of the system to be analyzed.

The variety of systems and structures in a nuclear facility are many. The frequency of importance can range from a low of 2 Hz in the soil structure interaction for soft soil to a high of above 50 Hz in a highly nonlinear design with impact during large vibration motions. In generating the spectra consistent time history, care must be exercised in taking each category of the problems into account. At high frequency, higher than 33 Hz, no frequency content should be allowed for all damping values. At and above the natural frequency of soil-structure interaction model, but below 33 Hz, time history should be developed with emphasis on the predominate damping value of the major systems and structures for the respective earthquake conditions (either NR6 or SSE). At and below the natural frequency of the soil interaction model the emphasis of the time history generation should be on the damping value of either the soil or the structure.
Often times a system, such as the reactor coolant system, needs to be integrated with another system, such as the supporting concrete structure, to account for the important interaction effect. This results in a very complex model for analysis. Furthermore, due to the presence of structural nonlinearities, a time history analysis may be necessary. A long duration time history input is not only unnecessary, but may be prohibitively expensive. Any action to reduce the size or simplify the model for economical compensations compromises the objectives of achieving a sound design qualification. The time history input needs only to have enough duration to envelope the design response spectrum. It can be shown that for this purpose a time history input longer than 6 seconds can be used conservatively.

The time phase relationships between input components are important to the structure and systems response for the time history components generated using real earthquake records, proper time phase relationships can be maintained by comparing with the real record but adjusting for the unusually richness of the frequency contents of the design response spectrum. For the time history components generated from other artificial means, a comparison of the time phase relationships with an ensemble earthquake records may be necessary.

Finally, the digitization time step of the time history motion ought to be consistent with the integration time steps used in generating the time history analysis of a complex structure which possess highly nonlinear characteristics. This will ensure that the solution using this time history input will be convergent and meaningful.
REFERENCES


