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AUTOMATED GENERATION OF SPECTRUM-COMPATIBLE ARTIFICIAL TIME HISTORIES *

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Criteria for the seismic design of nuclear power plants are usually defined in the form of response spectra, and it is often necessary to generate artificial time histories of ground motions to 'match' these spectra. A recently developed automated iterative procedure employing a combination of frequency- and time-domain techniques in any desired sequence for the development of spectrum-compatible artificial time histories is presented. The procedure employs four basic steps: (1) generation of an initial (starting) time history using either sinusoidal superposition with an envelope function or specification of a real time history of a recorded ground motion; (2) manipulation of the amplitude and phase of the Fourier transform representation of this time history, and generation of successive time histories which have response spectra converging to the target design spectrum; (3) manipulation of the amplitude and phase of the Fourier transform representation only locally in areas where the peaks of the computed spectrum have larger magnitudes of deviations than desirable; and (4) manipulation of local areas of the latest time history. Computer program EDAC/SEQGEN, which completely automates the above steps, is described. Results are presented for the development of two artificial time histories with corresponding spectra matching the target USNRC Regulatory Guide 1.60 response spectra within about 5–7%.

1. Introduction

The basic requirements that generally need to be satisfied in the development of artificial time histories which are compatible with a given design response spectrum are as follows.

(1) The computed response spectrum (CRS) obtained from the generated artificial time history should match the given target design response spectrum (DRS) as closely as possible.

(2) The generated artificial time history should have a peak ground acceleration equal to that defined for the site.

(3) The generated artificial time history should have the desired overall shape, duration, and frequency content.

Several authors have tried different approaches in the frequency and time domains to meet the above requirements [1–8]. However, it has been found to be difficult to achieve the desired objective of a very close match between the computed and the target spectra while at the same time satisfying the other requirements listed above. The purpose of this paper is to describe a procedure which better meets the above requirements by using an automated and integrated approach. The time histories are developed using a four-step procedure which employs both frequency domain and time domain techniques as listed below.

(1) Generation of initial (starting) time history using sinusoidal superposition with an envelope function.

(2) Manipulation of both the amplitude and phase of the Fourier transform representation of this time history in accordance with criteria formulated from comparison of a computed response spectrum and the target design response spectrum. Successive new time histories are generated having response spectra converging to the target design response spectrum.

(3) Manipulation of the amplitude and phase of the Fourier transform representation only locally in areas

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where the peaks of the computed spectrum have larger magnitudes of deviations.

(4) Manipulation of local areas of the latest time history at times where maximum response occurs.

A computer program EDAC/SEQGEN [9], with the above steps automated so that they can be used in any possible sequence, was developed.

2. Description of procedures for the generation of artificial time histories

2.1. Starting time history

As a starting time history, either a real history of a recorded earthquake or an artificial time history can be used. A starting artificial time history is generated by using an approach somewhat similar to the approach used in ref. [1] and described below.

The earthquake acceleration is defined as

$$\ddot{z}(t) = \sum_{n=1}^{N} A_n \cos\left(\frac{2\pi n t}{T} + \phi_n\right), \tag{1}$$

where T is the duration of the earthquake, and the coefficients A_n are defined in terms of the Fourier transform of the principal part of $\ddot{z}(t)$, as follows:

$$A_n = \frac{2}{T}\left|F_{\ddot{z}_\mathrm{p}}\left(\frac{2\pi n}{T}\right)\right|, \tag{2}$$

where

$$F_{\ddot{z}_\mathrm{p}}(\omega) = \int_0^T \ddot{z}_\mathrm{p}(t)\mathrm{e}^{-\mathrm{i}\omega t}\,\mathrm{d}t\,. \tag{3}$$

The number of terms N is chosen so that the generated time history includes all desired frequencies of interest. The phase angles ϕ_n are chosen as a set of N independent random numbers on the interval $(0, 2\pi)$.

2.2. Selection of an envelope function

After a real or an artificial time history has been selected, the next step is to select an envelope function which defines the shape and general characteristics of time history. The envelope function is arbitrary but can be chosen, as shown in fig. 1, to define the overall duration (ABCDE), build-up (AB), duration of intense motion (BC), and decay (CDE) of several earthquake types. Different types of envelope functions have been suggested in the literature [1,3,6–8]. One of the reasons for using an envelope function in some studies, in addition to defining the above mentioned shape and other general characteristics of the time history, has been to introduce non-stationarity to an assumed stationary random process used to define the motion [7,8].

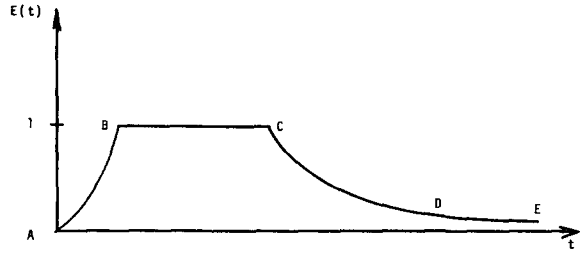

Fig. 1. Acceleration time history envelope.

2.3. Spectra matching techniques

The techniques described here can be used for matching the response spectrum computed from the artificially generated time history and the target response spectrum for a specified value of damping. However, an earthquake with a response spectrum which successfully envelopes one target curve for a given value of damping may not in general produce response spectra which envelop the target curves for other damping ratios.

2.3.1. Manipulation of the amplitude of Fourier transform for overall matching

The Fourier transform F_0 of the initial (starting) time history, or F_M of the time history generated at any iterative step M, is obtained by using the discrete Fourier transform procedure described in ref. [4]. This F_0 (or F_M) is then modified in accordance with the ratio of the value for a frequency ω_k of the response spectrum computed from the time history generated at this step and the corresponding value for the same frequency of the target design response spectrum by using

$$F_{M+1} = F_M/R(\omega_k, \xi)\,, \tag{4}$$

where

$$R(\omega_k, \xi) = \frac{\mathrm{CRS}(\omega_k, \xi)}{\mathrm{DRS}(\omega_k, \xi)}, \tag{5}$$

$\mathrm{CRS}(\omega_k, \xi)$ = computed response spectrum value at frequency ω_k, damping ξ
$\mathrm{DRS}(\omega_k, \xi)$ = design response spectrum value at frequency ω_k, damping ξ.

2.3.2. Manipulation of the phase of Fourier transform for overall matching

This is accomplished by changing the set $\{\phi_n\}$ of random numbers to a new set. No definite rules were developed for this manipulation of phase angles: judgment is primarily used for this purpose. The phase distribution of the Fourier transform of the time history at the last iterative step is examined. If the phase angles are not uniformly distributed in a desirable fashion, with some frequency ranges having higher density then others, a redistribution is carried out so that the distribution is more uniform for the next iterative step.

2.3.3. Local manipulation of the amplitude and phase of Fourier transform

To obtain a closer match between the CRS and the target DRS, the amplitude and phase angles are manipulated in local areas where peaks occur with relatively large deviations between CRS and DRS. The amplitudes are manipulated if CRS > DRS, and the phase angles are manipulated if CRS < DRS.

A linear interpolation procedure is used for the manipulation of the amplitudes. Fig. 2 shows a comparison of the CRS and the target DRS. The ratio $R(\omega_k, \xi)$ of the two spectra is computed at the frequency ω_k where a closer match is required. Ratios $R(\omega_{k-1}, \xi)$ and $R(\omega_{k+1}, \xi)$ are also computed. A linear interpolation is then carried out to modify the amplitude of the Fourier transform of the time history at the previous iterative step according to this ratio from $\frac{1}{2}(\omega_k + \omega_{k-1})$ to $\frac{1}{2}(\omega_k + \omega_{k+1})$. This

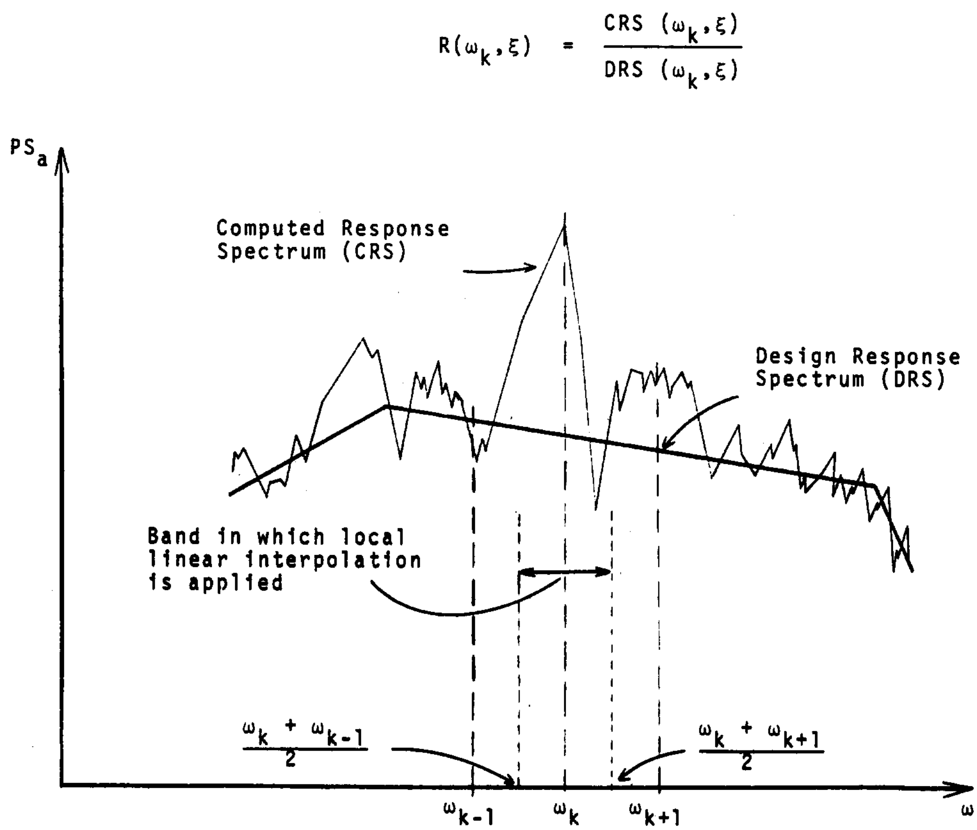

Fig. 2. Spectrum matching for local areas.

is performed locally for only those locations where a closer match is desired and where CRS is greater than DRS.

For those locations where the CRS is smaller than DRS and a closer match is required, the phase angles of the Fourier transform of the time history at the previous iterative step are modified. An attempt is made to modify these phase angles in such a way that a shift at frequency ω_k occurs equivalent to the value of $\Delta\omega = \omega_{k+1} - \omega_k$.

2.3.4. Manipulation of local areas of the time history

Final manipulations are carried out with the time history of the latest iterative step to obtain the desired final match between the response spectrum computed from this time history and the target design spectrum. The acceleration values in the local areas of the time history at times where the peaks of the computed spectra to be modified occur are modified according to the ratio $R(\omega_k, \xi)$ of the CRS to the target DRS.

The above four steps can be repeated in any desired sequence using automated computer techniques until a desired convergence between the response spectrum computed from the generated time history and the target response spectrum is obtained.

3. Results

Using the procedures described in the above section, two different artificial time histories of ground acceleration were generated to match the target USNRC Regulatory Guide 1.60 response spectrum for 1% damping.

The first time history, ATH01, was generated from an artificial initial (starting) time history. This artificial initial time history was obtained by using sinusoidal superposition with an envelope function as described in section 2. The frequency and phase angle contents of this initial time history were selected after an examination of several previously recorded earthquakes so that the generated artificial time history was representative of real earthquakes. A combination of the four steps described in section 2 was used for generating the final time history. The duration of the final time history ATH01 is 30 sec, and it consists of 3 sec of build-up of motion, 15 sec of intense motion, and 12 sec of decay. The time history consists of 3000 points and is digitized at a uniform time increment of 0.01 sec. Fig. 3 shows a plot of ATH01, and fig. 4 shows a comparison of the target USNRC response spectrum and the spectrum from ATH01 for

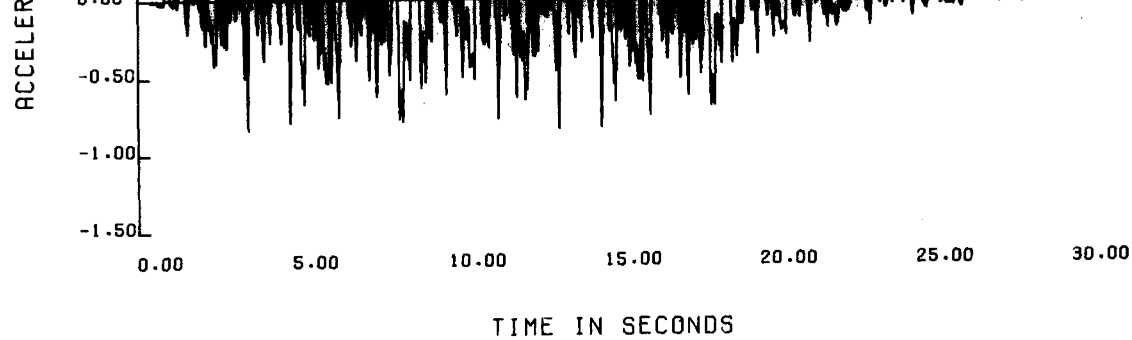

Fig. 3. Artificial time history ATH01.

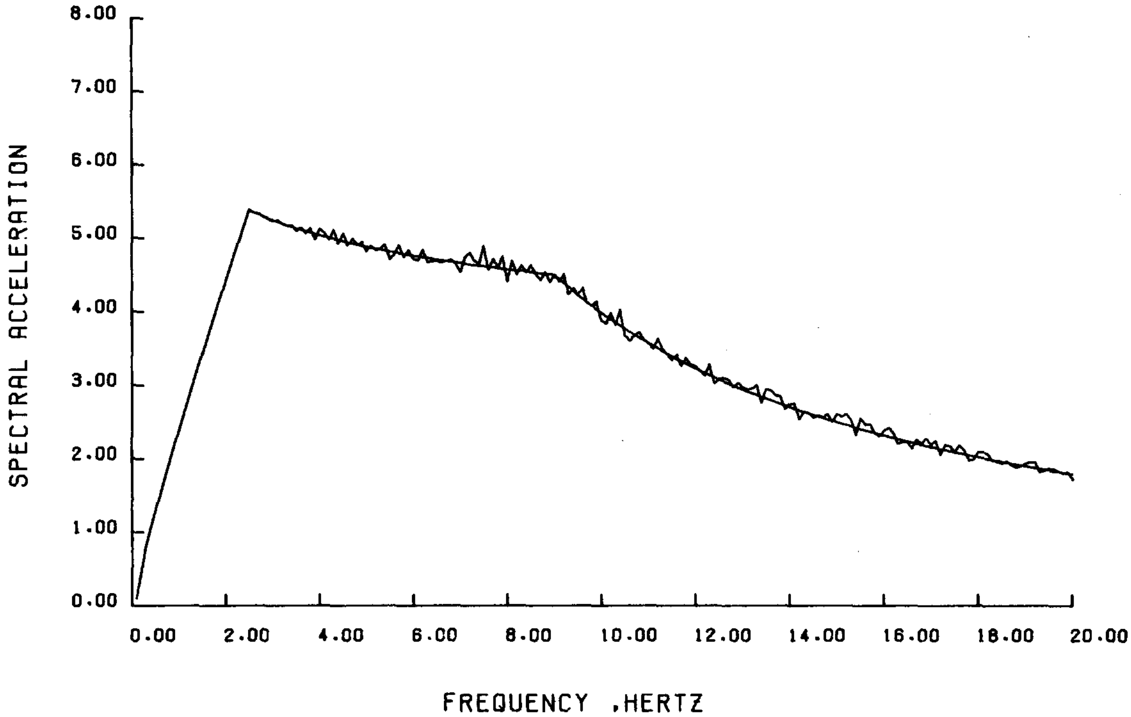

Fig. 4. Comparison of spectra – ATH01 and USNRC (damping ratio = 0.01).

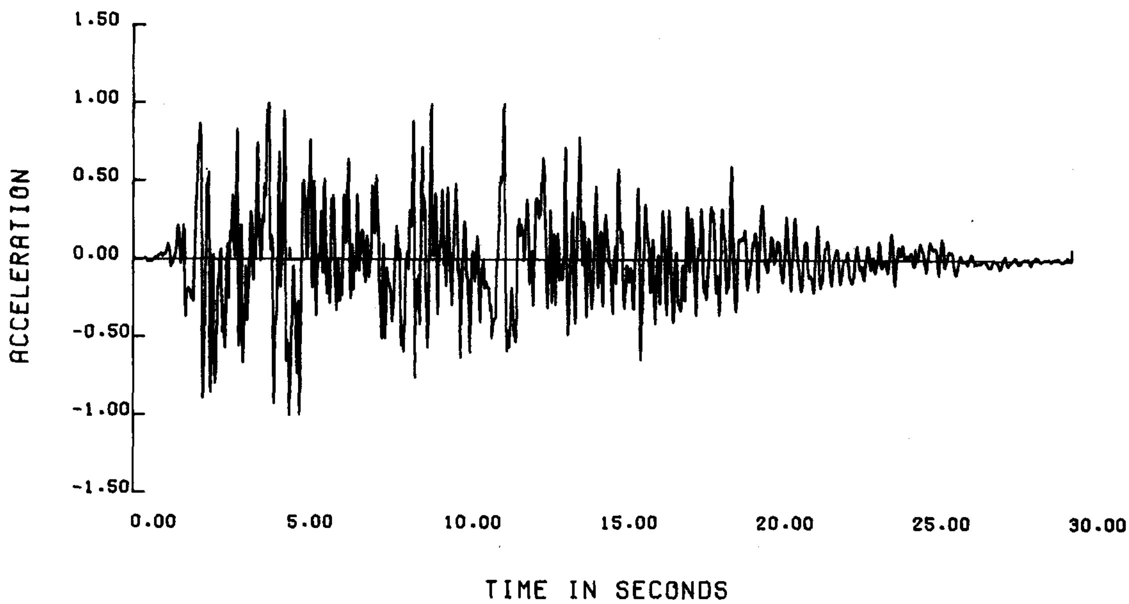

Fig. 5. Artificial time history ATH02.

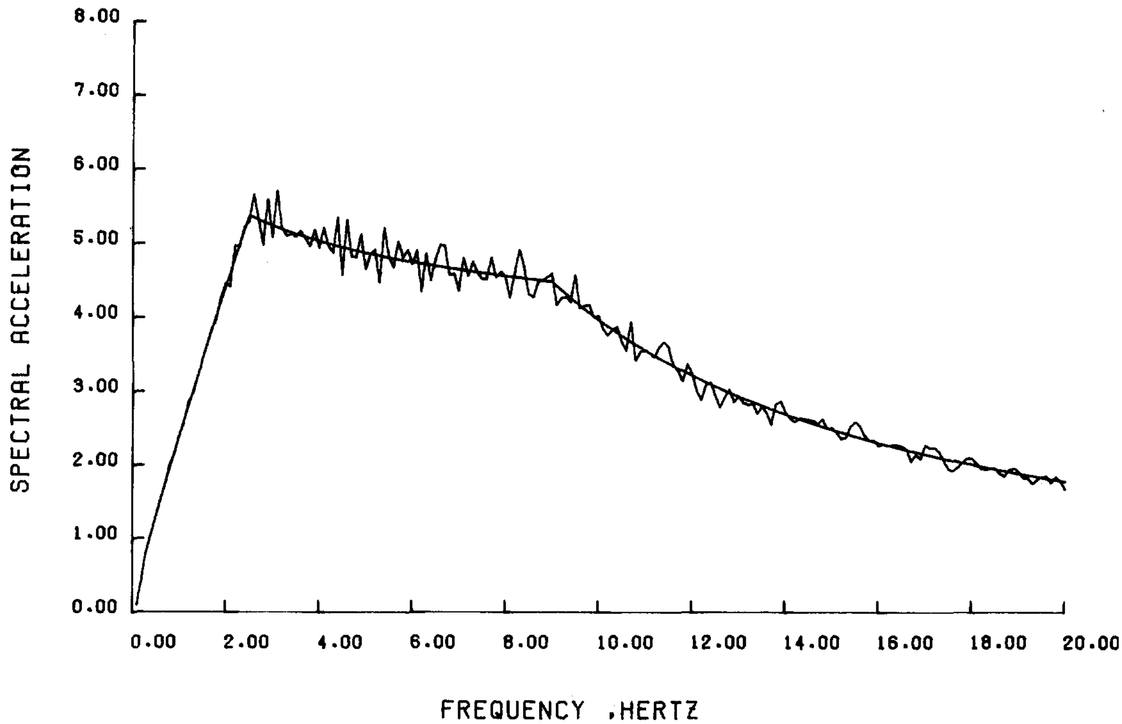

Fig. 6. Comparison of spectra – ATH02 and USNRC (damping ratio = 0.01).

1% damping. This latter spectrum was calculated at a uniform frequency interval of 0.01 sec for frequencies from 0.1 to 20 cps. The maximum difference between the response spectrum from artificial time history ATH01 and the USNRC spectrum is approximately 6%.

The second artificial time history, ATH02, was generated by starting from the 1940 El Centro earthquake, NS component. From this point on a procedure similar to that followed for ATH01 was used to modify this time history to produce the desired spectrum. This second time history, ATH02, is shown in fig. 5 and the corresponding spectrum is compared with the USNRC spectrum for 1 percent damping in fig. 6. The maximum deviation is about 9%, and the match is much better for the first time history, as can be seen from a comparison of figs. 4 and 6.

4. Summary and conclusions

An automated procedure employing both frequency domain and time domain techniques was applied to the generation of two artificial time histories to match the target USNRC Regulatory Guide 1.60 response spectrum for 1% damping. The first time history, ATH01, was generated from an initial (starting) time history artificially obtained by using sinusoidal superposition with an envelope function. The second time history, ATH02, was generated from the 1940 El Centro earthquake, NS component. As the results indicated, the match against the target 1% USNRC response spectrum was better for ATH01 than for ATH02. The reason for the difference in the behavior of the two artificially generated time histories is likely due to the presence of higher frequency components in ATH01.

The primary reasons for success in obtaining a very close match between response spectra obtained from an artificially generated time history and a target design response spectra are as follows.

(1) A judicious combination of frequency domain and time domain techniques was employed.

(2) An improved manipulation of both the amplitudes and the phase angles of the Fourier transforms was carried out, both for overall match as well as local

match. For example, the use of linear interpolation procedure for local match is an improvement over previous procedures.

(3) Use of higher frequency components was found to be useful in obtaining a better match between computed and target spectra.

(4) Manipulation of time history acceleration values was found to be helpful in obtaining the final convergence.

(5) Use of efficient techniques for generating Fourier and inverse Fourier transforms as well as response spectra made it possible to perform a number of iterations using much less computer time than in many previous studies.

(6) Complete automation of every step of the procedure and the inclusion of versatile plotting options considerably reduced the engineering time required to carry out the necessary iterations. This provided a better control over the complete procedure and helped in achieving additional savings of engineering time.

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