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DEVELOPMENT AND APPLICATION OF REALISTIC EARTHQUAKE TIME HISTORIES COMPATIBLE WITH MULTIPLE-DAMPING DESIGN SPECTRA

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SUMMARY

This paper describes the development and application of a new method for generation of realistic synthetic earthquake time histories compatible with multiple-damping design spectra. The effectiveness of this new method is demonstrated by applying it to adjust actual earthquake time histories to match the design spectra while minimizing perturbations on their characteristics. The paper also demonstrates that seismic responses of structures based on such spectrum-compatible realistic time histories are consistent with those obtained from analyses using an ensemble of time histories.

INTRODUCTION

The current practice for seismic analysis and design of nuclear power plants requires time history analyses be performed to generate floor response spectra. Since the design seismic ground motions are usually prescribed in the form of smooth, multiple-damping, design respone spectra, the generation of time histories whose response spectra closely match the "target" design spectra are needed to reduce the large number of seismic time history response analyses which would otherwise be required. To date, most existing methods proposed in the literature for the generation of spectrum-compatible time histories are limited to matching only one (single-damping) target spectrum. Furthermore, these methods generally do not have a definitive algorithm to ensure convergence to the target spectrum through iterations.

In this paper, a new time history generation method (Ref. 1) which effectively removes the above-mentioned limitations, is described. An actual application of this new method to generate "realistic" design time histories for an actual nuclear power plant site is presented. The paper also demonstrates that the application of these realistic design time histories results in floor response spectra which are consistent with those obtained from the analysis based on the ensemble of time histories which form the basis of the design response spectra.

NEW TIME HISTORY GENERATION METHOD

The new method developed for generating synthetic time histories matching multiple-damping response spectra is based on the observation that the time at which the spectral response of a time history occurs, is not perturbed by a small adjustment made on the time history. Based on this observation, the small change in the response spectral acceleration value, $\delta R\ (\omega_i,\ \beta_k)$, at spectral frequency ω_i for spectral damping β_k can be related to the small adjustment $\delta a(t)$ on the initial input acceleration time history, a(t), through the Duhamel's integral:

$$\delta R_{ik} = \delta R(\omega_i,\ \beta_k) = \int_0^{t_i} \delta a(\tau)\ h_{ik}\ (t_i - \tau)\ d\tau \qquad (1)$$

where $h_{ik}\ (t)$ is the acceleration impulse response function for a single-degree-of-freedom oscillator with frequency ω_i, and damping ratio β_k; t_i is the time at which the spectral response occurs; and τ is the time lag. The task of adjusting a time history to match the target spectra is to solve Eq. (1) for $\delta a(t)$, given $\delta R(\omega_i,\beta_k)$.

For matching a set of target spectral values at N spectral frequencies for M spectral damping ratios, the solution of Eq. (1) can be transformed into the solution of a set of MxN linear algebraic equations by letting $\delta a(t)$ be a linear combination of a set of MxN prescribed linearly independent functions, $f_{j\ell}(t)$, as follows:

$$\delta a(t) = \sum_{j=1}^{M} \sum_{\ell=1}^{N} b_{j\ell} f_{j\ell}(t) \qquad (2)$$

in which $b_{j\ell}$ are unknown constant coefficients to be determined. From Eqs. (1) and (2), the set of linear algebraic equations become

$$\delta R_{ik} = \sum_{j=1}^{M} \sum_{\ell=1}^{N} C_{ijk\ell}\ b_{j\ell}\ ; \quad C_{ijk\ell} = \int_0^{t_i} h_{ik}\ (t_i - \tau\ )\ f_{j\ell}\ (\tau)\ d\tau \qquad (3)$$

It is obvious from Eq. (3) that in order to be efficient in computing $C_{ijk\ell}$, the function $f_{j\ell}\ (\tau)$ should be prescribed as:

$$f_{j\ell}\ (\tau) = h_{j\ell}\ (t_j - \tau) \qquad (4)$$

so that $C_{ijk\ell}$ are symmetric and can be computed by:

$$C_{ijk\ell} = \int_0^{t_i} h_{ik}\ (t_i - \tau)\ h_{j\ell}\ (t_j - \tau)\ d\tau\ ;\ t_i \leq t_j \qquad (5)$$

Having computed the coefficient matrix, Eq. (3) can be solved for $b_{j\ell}$ by standard linear equation solver; then, the small adjustment $\delta a(t)$ can be obtained from Eq. (2). The adjusted time history for each iteration, $a_1(t)$, can be obtained from the time history of previous iteration, $a_o(t)$, by

$$a_1\ (t) = a_o\ (t) + \delta a_o\ (t) \qquad (6)$$

By repeatedly applying the above iteration scheme, the desired accuracy of matching between the time history spectra and multiple-damping target spectra can be achieved.

GENERATION OF REALISTIC DESIGN TIME HISTORIES

Recent advances in the geological and seismological studies of earthquake ground motions (Ref. 2) have led to predictions of earthquake ground motions at a site with increasing accuracy based on the site-specific parameters relating to the source, source-to-site travel path, and local site conditions. This implies that when generating synthetic ground motions, these motions can no longer be treated as random motions without proper considerations given to the site-specific earthquake parameters. Recent engineering studies (Ref. 3) have also shown that some characteristics inherent in actual earthquake motions such as the distribution of differential phases is closely related to the appearance and intensity envelope of the motions. It is, thus, important to preserve the actual characteristics of recorded motions as much as possible when they are utilized to generate synthetic time histories to fit target design spectra.

Most of the methods for generation of synthetic time histories (e.g., Ref. 4) generally follow a frequency domain procedure to modify an initial input time history by repeatedly adjusting its Fourier amplitudes based on the ratios of the target spectral values to the time history spectral values at the matching spectral frequencies. As a result, the time history adjustment $\delta a_o(t)$ for each spectral frequency is a harmonic motion with uniform strength extended over the entire duration of the motion. This produces significant perturbations on the time history as well as the spectra. On the contrary, the new method described herein is a time domain procedure which recognizes the inherent time domain definition of response spectra and only adjust the time history locally at t_i, at which the spectral value occurs. As a result, the time history adjustment produces only localized perturbations on both the time history and the spectra. To illustrate this difference between the two methods, both methods are applied to adjust the same initial time history to fit a target spectrum which is the same as the initial time history spectrum except that the spectral values at 5 cps is raised by 50% from its initial value. The time history adjustments $\delta a_o(t)$ and the modified time histories $a_1(t)$ resulting from applying both methods are shown along with the initial time history $a_o(t)$ in Figs. 1 and 2. As shown, the frequency domain method results in a significant perturbation on the initial time history and the modified time history appears quite different from the initial time history; whereas the time domain method produces a localized peturbation around t_i and, as a result, the modified time history resembles closely the initial time history. The effect on the response spectrum due to the time history adjustment by both methods is demonstrated in Figs. 3 and 4. As can be seen, the time domain method results in almost an exact match and a localized spectral perturbation; whereas the frequency domain method does not.

SITE-SPECIFIC APPLICATIONS

In a recent site-specific study, this new time history generation method was applied to adjust two sets of actual earthquake recordings selected for matching site-specific target design response spectra of several damping values. These two sets of recordings are the Pacoima Dam records of the 1971 San Fernando earthquake and the Tabas records of the 1978 Tabas earthquake. The adjustment using one component of the Pacoima Dam records to generate a realistic design time history to match the site-specific spectra is presented here to demonstrate the effectiveness of this new method. The unmodified Pacoima acceleration time history which was used as the initial time history for modification, is shown along with its velocity and displacement time histories in Fig. 5. The acceleration response spectra for 2% and 5% damping are shown and compared with the target spectra in Fig. 6. The modified Pacoima spectrum-compatible time histories corresponding to those shown in Fig. 5 obtained by applying this new method, are shown in Fig. 7. Figure 8 compares the target response spectra with the time history spectra of the spectrum-compatible accleration time history. By comparing Fig. 5 with Fig. 7, and Fig. 6 with Fig. 8, it can be seen that the modified time histories closely resemble the realistic characteristics and appearance of the corresponding unmodified actual earthquake time histories, at the same time, the modified time history spectra closely match the target spectra.

Due to the close match to the multiple-damping target spectra that can be achieved using this new method, the applications of two different realistic, spectrum-compatible time histories as generated for seismic response analyses of structures can result in seismic responses which are mutually consistent with each other. The responses as obtained will also be consistent with the ensemble-averaged responses resulting from analyses using the input of the time history ensemble which forms the basis of the target design response spectra. This is demonstrated by the results obtained for the previously-mentioned site-specific study in which the modified spectrum-compatible Pacoima and Tabas time histories were both applied to generate the seismic time history responses of a structure. In that study, the responses of the structure were also computed using a random vibration analysis method (Ref. 5) with the input of the power spectral density function (PSDF) of the time history ensemble which forms the basis of the site-specific spectra. The ensemble-averaged PSDF used is shown and compared with the averaged PSDF of the two modified Pacoima and Tabas time histories in Fig. 9. As shown, the averaged time history PSDF is consistent with the ensemble-averaged PSDF. Representative 5% damped floor response spectra obtained from analyses using the modified Pacoima and Tabas time histories as input are shown and compared with the corresponding spectrum obtained from the analysis using the ensemble-averaged PSDF as input in Fig. 10. As can be seen, the floor response spectra of the time history responses are mutually consistent with each other, and they are also consistent with the ensemble-averaged floor response spectrum.

CONCLUSIONS

As demonstrated by the results presented in this paper, the new time history generation method can effectively be used to generate realistic design time histories whose response spectra closely match the multiple-damping, target design response spectra, and the final modified time histories as generated closely resemble the realistic characteristics of the actual earthquake ground motions which are used as the initial time histories for modifications. This unique feature of the method is due to the time domain adjustment procedure used by the method, which produces only small localized perturbations on both the time history and the response spectra. The seismic responses resulting from the use of such realistic, spectrum-compatible time histories are mutually consistent and they are also consistent with the ensemble-averaged responses. The site-specific applications have demonstrated this unique feature of the new method.

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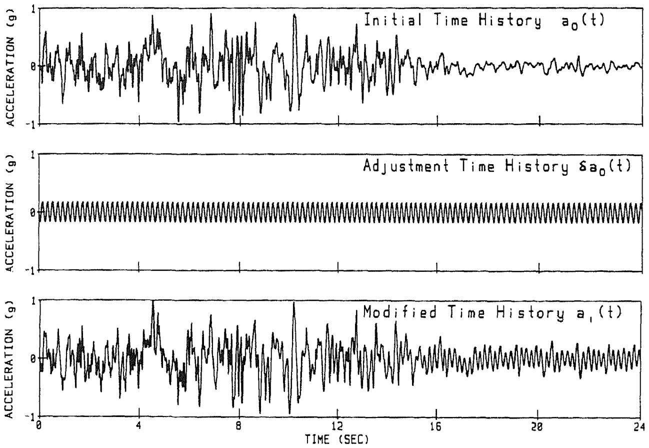

Fig. 1 Time History Adjustment by Frequency Domain Adjustment Procedure

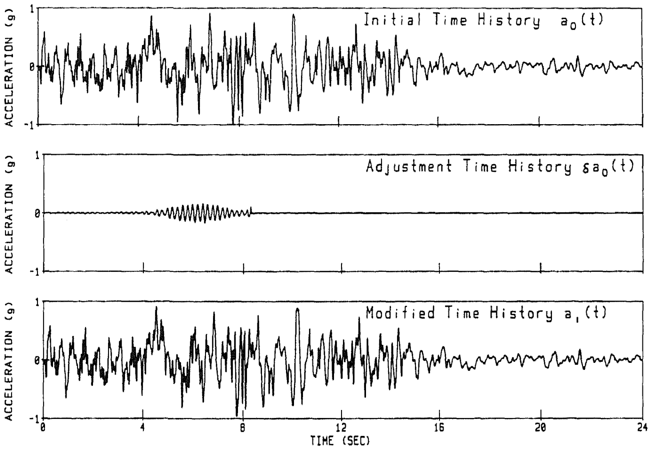

Fig. 2 Time History Adjustment by Time Domain Adjustment Procedure

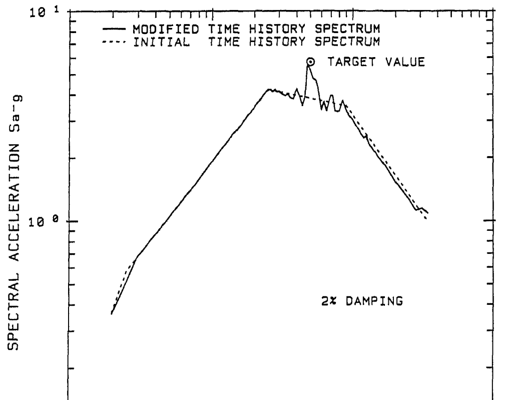

Fig. 3 Response Spectrum Matching by Frequency Domain Adjustment Procedure

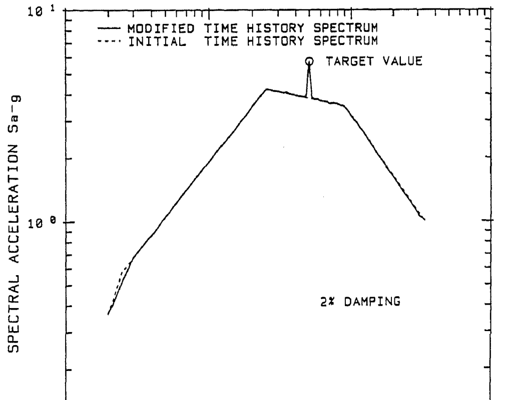

Fig. 4 Response Spectrum Matching by Time Domain Adjustment Procedure

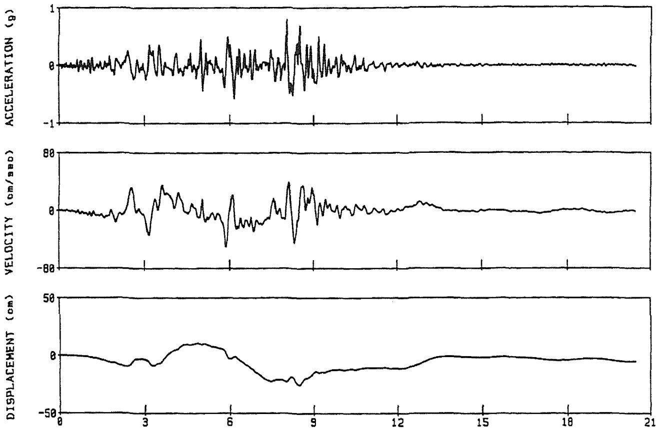

Fig. 5 Unmodified Pacoima Time Histories

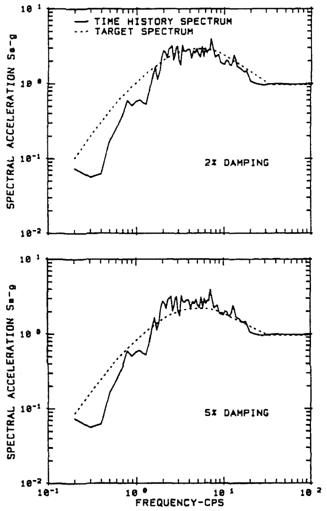

Fig. 6 Response Spectra of Unmodified Pacoima Time History

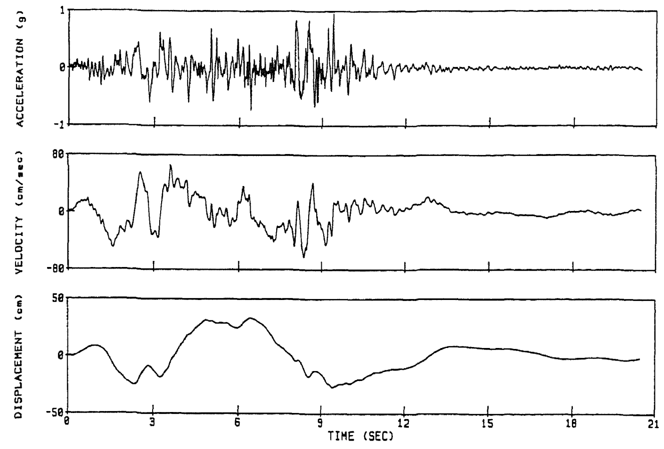

Fig. 7 Modified Pacoima Time Histories

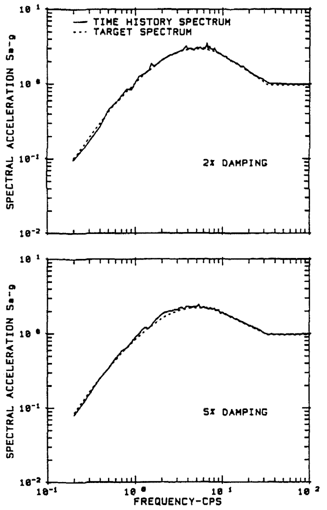

Fig. 8 Response Spectra of Modified Pacoima Time History

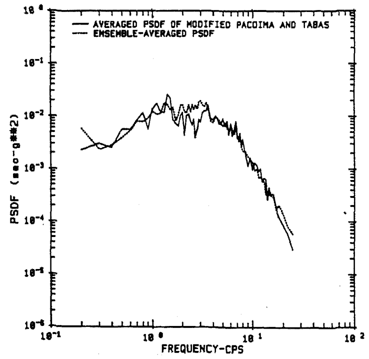

Fig. 9 Comparisons of Power Spectral Density Functions

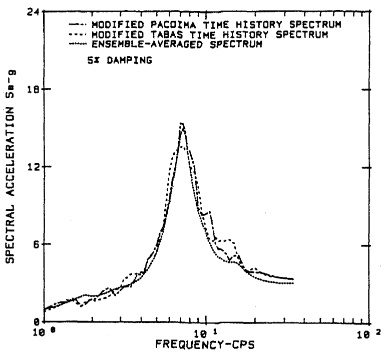

Fig. 10 Comparisons of Floor Response Spectra