INTRODUCTION

Since, the various structures, components and equipment of nuclear power plants have different damping values, in order to obtain realistic results in the response analysis of them, the use of input earthquake motions compatible with multiple-damping design response spectra is required. In this study, the problem of generation of an accelerogram compatible with a set of response spectra with different damping values will be examined. This approach also covers the case of synthetic accelerograms compatible with a single damping response spectrum.

Synthetic earthquake motions can be generated to be compatible with a single-damping response spectrum by the methods introduced by Theofanopoulos (1989). Fig. 1 shows an earthquake motion with magnitude 6.5 and distance to the fault 10 km which was generated to fit the design response spectrum proposed by Ohsaki (1979) which has been modified by the use of the frequency dependent factors proposed by Theofanopoulos (1989) to represent the motion along the major principal axis. This kind of input earthquake motion is required by the "Recommendations for the Aseismic Design of Nuclear Power Plants" in Japan. It can be noticed from Fig. 1 a rather good fitting of the response spectrum for damping 5% to the target one, but the spectra for dampings 1 and 3% do not match satisfactorily the target ones. However, when a synthesized earthquake motion is applied to a structural system composed of members with different damping characteristics, it is desired to be simultaneously compatible with design response spectra with different damping ratios.

A first approach to this problem was made by Masao et al. (1985). They tried to control the degree of matching of a synthetic earthquake motion to a double-damping response spectrum by defining the Fourier phase angles as non-linear function of frequency. The proper combination of that function's constants may control the fitting of the synthetic motion to the double-damping design response spectra, but results to a non-realistic waveform.

Lilhanand and Tseng (1987) developed as an extension of the method originally proposed by Kaul (1978) an iteration scheme that can improve the accuracy of spectral matching for multiple-damping target response spectra. They presented examples of synthetic motions that fit to a single and a double-damping target response spectra.

In this study this iteration scheme was refined and it was applied to improve the spectral fitting in the cases of single, double and for the first time of triple-damping target response spectra.
OUTLINE OF THE METHOD - REFINEMENTS

The basic assumption of the method is that the time at which the maximum response for a given circurlar freqency and damping value occurs, is not perturbed by a small adjustment $\delta a(t)$ of the original time history $a(t)$. The new time history for the $(n+1)$th iteration cycle can be obtained from the acceleration time history for the $n$th cycle as follows:

$$a_{n+1}(t) = a_n(t) + \delta a_n(t) \tag{1}$$

The small change to the acceleration time history $\delta a(t)$ will result to a small change of the spectral values given by:

$$\delta R(\omega, h_k) = \int_0^{t_{ik}} \delta a(\tau) I_{ik}(t_{ik} - \tau) \, d\tau \tag{2}$$

where $I_{ik}(t_{ik} - \tau)$ is the acceleration impulse response function for circular frequency $\omega_i$ and damping ratio $h_k$, and $t_{ik}$ is the time at which the maximum response occurs.

Let $S_0(\omega_i, h_k)$ denote the acceleration response spectral value of a synthesized earthquake motion and $S_0^{\text{TARGET}}(\omega_i, h_k)$ denote the target response spectrum at frequency $\omega_i$ and for damping $h_k$. Let also $S(\omega, h_k)$ be an integer whose value is 0 if the maximum absolute acceleration is positive and 1 if it is negative. The amount which the response acceleration time history must be altered at the time $t_{ik} = t(\omega_i, h_k)$ that attains its maximum value is computed by:

$$\delta R(\omega, h_k) = \left[ S_0^{\text{TARGET}}(\omega_i, h_k) - S_0(\omega_i, h_k) \right] (-1)^{S(\omega, h_k)} \tag{3}$$

In order to improve the fitting for $M$ natural frequencies and $N$ damping values, the solution of equation 2 for $\delta a(t)$ can be expressed as a combination of a set of $M \times N$ pre-selected, linearly independent functions. In this study, the acceleration impulse response of a single-degree-of freedom oscillator with circular frequency $\omega_i$ and damping $h_k$, back in time, starting from the maximum response time $t_{ik}$ was chosen to represent those functions.

In implementing the above procedure, Preumont (1984) adopted to multiply the correcting wave $\delta a(t)$ by a half-cosine window function $w(t)$:

$$w(t) = \begin{cases} \frac{\alpha}{2} \left(1 - \cos \frac{\pi t}{T_1} \right) & 0 \leq t \leq T_1 \\ \alpha & T_1 < t \leq T_d \end{cases} \tag{4}$$

where $T_1$ is the beginning of the strong motion interval and $T_d$ is the total duration of the motion. The beginning of the strong motion interval $T_1$ can be obtained from the relationships proposed by Theofanopoulos et al. (1987). This implementation provides a smooth start and offers the possibility to control the peak value of the correcting wave by means of the relaxation parameter (a). This is necessary, in order to prevent any strong departure from the basic assumption of unchanged time of occurrence of the maximum acceleration response. The value of (a) was assumed to be:

$$a = \frac{\delta R(\omega_i, h_k)}{S_{00}(\omega_i, h_k)} \tag{5}$$

where $\delta R(\omega_i, h_k)$ represents the maximum value of the $\delta R(\omega_i, h_k)$ calculated by equation 3 and $S_{00}(\omega_i, h_k)$ is the maximum spectral value of the correcting wave $\delta a(t)$ for all circular frequencies and damping ratios.
A typical correcting wave is shown in fig. 2. The peak value of the correcting wave is one order of magnitude smaller than that of the accelerogram to be corrected. Fig. 3 shows the correcting wave resulted after multiplying by the half-cosine window function of equation 4. It can be observed a smooth built-up of the correcting motion and a decrease of its peak value due to the use of the relaxation parameter (a). By repeated application of the above iteration scheme to the acceleration time history, the desired accuracy of matching between the calculated spectra and the target ones, can be achieved.

To assure the convergence of the iteration scheme, the added wave $\delta a(t)$ must have small amplitudes to keep undisturbed the time $t_k$ at which the response is obtained. To achieve this requirement, in the cases when the $\delta R(\omega_i, h_k)$ is large, different target spectra at each iteration were set. These pseudo-target spectral values were increased or decreased gradually at each iteration cycle to obtain at the last one, the originally set target spectrum. In the cases of $\delta R(\omega_i, h_k)$ values less than 1% of the correspondent target spectral values the above mentioned modification was not performed.

APPLICATION EXAMPLES

The effectiveness of the iteration scheme described in the previous paragraphs is demonstrated by the following three examples.

Single-damping design response spectrum

The target response spectrum was that proposed by Ohsaki (1979) for magnitude 6.5 and distance to the fault of 10 km. This spectrum was multiplied by the frequency dependent factors proposed by Theofanopoulos (1989) to represent the motion along the major principal axis. The number of matching frequencies for damping 5% was equal to 100. The earthquake motion was generated by superposition of sinusoidal waves with a set of phase angles uniformly distributed in the interval $(0, 2\pi)$. The non-stationarity of the motion was obtained by the use of the envelope function (shape 4) proposed by Theofanopoulos et al. (1987). The response spectrum of this motion approached the target one after repeated correction of the Fourier amplitudes. The resulted time history is shown in fig. 4. It can be noticed a fairly good fitting of the response spectrum of the simulated motion to the target one. However, in some matching frequencies the marginal error was more than 10%. In order to improve the spectral matching, the iteration scheme described above was applied five times. The results are shown in fig. 5. It can be observed that the spectrum of the generated time history converges to the target one with high accuracy. The waveform of the earthquake motion was remained unaltered and still attains realistic peak value and duration time.

Double-damping design response spectra

The common practice for the design of nuclear power plants in Japan requires response analysis in two levels, which may be termed as $S1$ and $S2$. An earthquake motion of magnitude 7.0 and distance to the fault 20 km that correspond to $S1$ level, was generated to be compatible with design response spectra for dampings 1 and 5%. The design response spectra proposed by Ohsaki (1979) were modified to represent the motion along the major principal axis. An earthquake motion was generated to fit the design response spectrum with damping ratio 5%. The generated motion along with the target and the calculated spectra are shown in fig. 6. Although, the spectral fitting for damping 5% is fairly good, for damping 1% the maximum marginal error is about 60%. The number of matching frequencies for both dampings was equal to 150. The iteration scheme described in the previous paragraphs was applied 6 times and the results are summarized in fig. 7. The spectral fitting was obviously improved and the maximum marginal error is about 2% for both damping values.
Triple-damping design response spectra

The earthquake motion of magnitude 6.5 and distance to the fault 10 km of fig. 1 generated to fit the design response spectrum with damping 5%, was corrected by the iteration scheme described above to be simultaneously compatible with the design response spectra with damping values of 1, 3 and 5%. The number of matching frequencies for all three damping values was set equal to 100. After 12 cycles of iteration, the spectra of the calculated time history converge to the target spectra for all matching frequencies and damping values with less than 1% of marginal error. The resulted earthquake motion along with the target and the calculated spectra are shown in fig. 8. It can be observed a really excellent fitting of the calculated and target spectra for all frequencies and damping values.

RESPONSE ANALYSIS

The basic philosophy when constructing Nuclear Power Plants is that they must maintain their structural integrity against any conceivable seismic force likely to occur at the site, so that no earthquake leads to a major accident. The difference in the response of a Boiling Water Reactor (BWR) building due to the synthesized motions, with magnitude 7.0 and distance to the fault of 20 km, compatible with single-damping (5%) and multiple-damping (1 and 5%) design response spectra, was examined.

A typical BWR building was modeled by a lumped-mass system enclosed in a massless rigid foundation as shown in fig. 9. In order to obtain the impedance functions and the effective input motions of foundation, the equations proposed by Tohdo et al. (1986) based on the results of the complete 3-dimensional Green's function method, were utilized. The depth to the half width ratio of the foundation was taken equal to 0.5 and the shear wave velocity of the elastic half-space was 500 m/sec.

Moreover, linear dynamic response analysis of the lumped-mass model of fig. 9 was accomplished. The results of this analysis will be presented as displacement, velocity and acceleration response spectra (floor spectra) at OPP point (see fig. 9) for damping value of 1%. Comparison of these spectra due to synthetic earthquake motions compatible with single-damping (5%) and multiple-damping (1 and 5%) design response spectra are shown in fig. 10 to 12, respectively. A great difference in the response due to these motions can be noticed. The response values at OPP due to synthetic motion compatible with a single-damping design response spectrum exceed, at some periods, those due to synthetic motion compatible with multiple-damping design response spectra by about 30% for spectral acceleration, 58% for spectral velocity and 70% for spectral displacement.

CONCLUSIONS

It can be concluded that earthquake motions, synthesized to be compatible with multiple-damping design response spectra, are the most appropriate for the response analysis of Nuclear Power Plants, because they lead to more conservative results by eliminating or lowering the spikes that appear at floor response spectra due to earthquake motions compatible with single-damping design response spectra. The decrease of the floor response spectral values to a reliable level, obtained by the use of input earthquake motions compatible to multiple-damping design response spectra, implies a reduction in the cost of construction, that in the case of Nuclear Power Plants may be considerably high.

REFERENCES


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![Fig. 1. Simulated earthquake motion](image1)

![Fig. 2. Example of a correcting wave](image2)

![Fig. 3. The correcting wave after applying the half-cosine window function in time domain](image3)

![Fig. 4. The same motion of fig. 1 and comparison between the target and the calculated response spectra for damping 5%](image4)

![Fig. 5. Final time history after 5 iterations](image5)
Fig. 6. Simulated earthquake motion ($M=7.0$, $R=20$ km) Fig. 7. Final time history after 6 iterations

Fig. 8. Final time history after 12 iterations and comparison between the target and the calculated response spectra for damping 1, 3 and 5%

Fig. 9. Model of a BWR building.

Fig. 10-12. Comparison between the displacement, velocity and acceleration response spectra at OFF due to input motions compatible with a single-damping (5%) and multiple-damping (1 and 5%) design response spectra.