Stochastic Seismic Floor Response Analysis Method for Various Damping Systems

Y. Kitada, M. Nakai

Nippon Atomic Industry Group Company Ltd., Kawasaki, Japan

M. Ogata

Toshiba Corporation, Yokohama, Japan

J. N. Kanda

University of Tokyo, Tokyo, Japan

ABSTRACT

A study on the stochastic seismic response analysis method, which is applicable for estimation of floor response spectra, is carried out. It is pointed out as a shortcoming in the stochastic seismic response analysis method, that the method tends to overestimate floor response spectra for low damped system, for example having 1 % of critical damping ratio.

An investigation on a cause of the shortcoming is carried out and some improvements in this method are made by taking correlation of successive peaks in a response time history into account. An application of the improved method to a typical BWR reactor building is carried out. The resultant floor response spectra are compared with those obtained by the conventional time history analysis.

INTRODUCTION

The floor response spectra, to be used in aseismic design of important equipments and piping systems of a nuclear power plant (NPP), are generally computed by deterministic time history analysis using an artificial time history, which satisfies the design earthquake ground motion spectrum. However, it has been pointed out that the time history analysis evaluates earthquake response only for a sample time history, whereas many design spectrum compatible time histories can be considered. For this reason, probabilistic analysis method which computes floor response spectra is proposed [1]. The method can evaluate floor response spectra with some confidential levels of band width, thus the method has a capability of estimating reliability of floor response spectra (FRS) computed by the time history method. Furthermore, because the method requires less computer time in the response spectrum computation than the time history method, it can contribute computer time saving. In the method, FRSs are calculated probabilistically (or stochastically) from the design ground motion response spectrum, based on the random response theory. The resultant FRSs obtained by this method have good consistency with those obtained by the time history method for high damped system, for example having 10 % of critical damping, as shown in Fig.1. The figure shows response spectrum estimated by the stochastic method from a power spectral density (PSD) for a stationary random process and response spectra calculated by 10 random time histories which have compatible PSD with the stationary random process. However, as can be seen in Fig.2, for low damped system with 1 % of damping ratio, this method tends to overestimate a response spectrum. Therefore in order to apply the stochastic method widely and satisfactorily, some improvements on the method should be required for its applicability to a low damped system.

IMPROVEMENT ON THE ANALYSIS METHOD

A feature of the random response theory to be applied, is in the mutual conversion between PSD and response spectrum (RS) of a time history. In this conversion process, peak values in a response time history of one degree of freedom (1 DOF) system, of which maximum value constitute a frequency component of the RS, are calculated under the assumption that peaks in a response time history are independent each other. However, a peak in a response time history tends to be affected to some degree by the previous peaks in the time history. This tendency becomes more evident for low damped system, for example having 1 % of critical damping ratio. Figure 3 shows sample response time histories of 1 DOF systems with 5 Hz of natural frequency. The top of the figure shows a response of 10 % damping system and the bottom shows a response of 1 % damping system. The correlation functions of both time histories are shown in Fig.4. In this figure, we can see the strong correlation among response peaks in response time history of low damped system.

Yang & Shinozuka [2] have studied on the method of introducing the effect of previous peaks in a response time history on a response peak of interest. They assumed that a peak in a response time history is affected by a peak preceding just one step. They estimate the effect in the form of correlation coefficient, which is obtained as a correlation value between successive peaks in the response time history. The multivariate probability density function for the successive peaks, 0 and 1 is given as;

$$P(\eta_0, \eta_1) = \frac{\eta_0 \cdot \eta_1}{1 - \rho^2} I_0 \left[\frac{\rho \eta_0 \eta_1}{1 - \rho^2} \right] \exp \left(\frac{-(\eta_0^2 + \eta_1^2)}{2(1 - \rho^2)} \right) \quad (1)$$

where, ρ represents correlation coefficient $[\exp(-2\pi h)]$, h means damping ratio, η_0 means the peak value of interest, η_1 means the value of the peak just preceding the peak 0 and I_0 means 0-th Bessel function, respectively.

The probability that η_1 is less than η and η_0 is greater than η is defined as a following conditional probability :

$$P(\eta_0 > \eta \mid \eta_1 < \eta) = P(\eta_0 > \eta \cap \eta_1 < \eta) / P(\eta_1 < \eta) \\ = \int_{\eta}^{\infty} d\eta_0 \int_0^{\eta} d\eta_1 P(\eta_0, \eta_1) / \int_0^{\eta} d\eta_1 P(\eta_1) \quad (2)$$

With this equation, the probability that all N peaks in a time history are less than η , which means probability distribution function of maximum peak, $Pe[\eta]$, can be expressed as follows ;

$$Pe(\eta) = [1 - P(\eta_0 > \eta \mid \eta_1 < \eta)]^N \\ = \exp \{-N \cdot P(\eta_0 > \eta \mid \eta_1 < \eta)\} \\ = \exp \{-N \cdot P(\eta_0 > \eta \cap \eta_1 < \eta) / P(\eta_1 < \eta)\} \quad (3)$$

In the case when power spectral density function has a sharp peak with ν of dominant frequency, number of peaks in a response time history, having T of duration time, is given by the following relation ;

$$N = \nu T \quad (4)$$

In the present study, the probability distribution function for the maximum peak is obtained by substituting Eq.(1) and Eq.(4) into Eq.(3) and by performing the integration. The probability distribution function of maximum peak is given in the following form ;

$$Pe(\eta) = \exp \left\{ -\nu T \cdot (1 - \rho^2) \sum_{k=0}^{\infty} \rho^{2k} \sum_{r=0}^k S(r) \left(\frac{1 - \sum_{j=0}^k S(j)}{1 - e^{-\eta^2/2}} \right) \right\} \quad (5)$$

$$\text{where,} \quad S(r) = \exp(-\beta) \cdot \beta^r / r! \\ \beta = \eta^2 / 2(1 - \rho^2)$$

Naturally, when every peak in a time history is independent of other peaks, the value of correlation function ρ is zero and Eq.(5) can be reduced to the following form ;

$$P_e(\eta) = \exp \left\{ -\nu T_e^{-\eta/2} \right\} \quad (6)$$

Equation (6) is in the same form as the conventional form applied in the Ref.[1]. The expected value of peak factor for the maximum peak in a time history, $E(\eta)$ or n can be evaluated by the following equation.

$$E[\eta] = \int \eta P_e(\eta) d\eta \quad (7)$$

The relationship between peak factor, $E[\eta]$ which calculated by applying probability distribution function defined in Eq.(5), and the number of peaks, N (or νT), are investigated for various damping ratios. The results are shown in Fig.5 together with the conventional peak factor calculated from Eq.(6). In this figure, we can see that peak factors calculated from Eq.(5) are lowly evaluated as compared with the factor calculated from Eq.(6), which regards every peak in a time history as independent each other. The trend becomes more significant for lower damping systems. It can be said that the applicability of the present probabilistic floor response estimation method to a low damped system is promising.

The value $\eta(T)$ is used to estimate the maximum seismic response for a natural period point on a response spectrum, $X_{\max}$, together with a standard deviation of response time history, $\sigma(T)$, which is estimated by using a power spectrum of an input time history and a transfer function for 1 DOF vibration system, having a corresponding natural period and a damping ratio.

$$X_{\max} = \eta(T) \times \sigma(t) \quad (8)$$

Figure 7 shows an application example of the present method to stationary random process. Analyses are made under the same conditions as those shown in Fig.1 and Fig.2. With a comparison between Fig.1 and Fig.6, it is clear that good consistency between response spectra estimated by the present method and by the time history method, keep nearly the same scheme for high damped system. Moreover, with comparison between Fig.2 and Fig.7, the relation can be said to be considerably improved to have good consistencies between resultant FRSS obtained by the present method and by the time history method, for a low damped system.

APPLICATION

As an application example, floor response spectra for a typical BWR reactor building, sited on a rock field, having 750m/sec of shear wave velocity, are estimated by the present method. Procedure of the analysis is shown in Fig.8. A feature of this procedure is in the introduction of power spectrum in place of acceleration time history to the earthquake response analysis. Because the conversion between a power spectrum and a response spectrum is carried out based on stochastic theory, some band width in PSDs or RSs of conversion results can easily be introduced for various confidential levels. And if the power spectra, described in this figure, are replaced by corresponding time histories, the procedure turns to an aseismic design analysis procedure, currently applied as a Japanese NPP design practice. In this application example, the Ohsakispectrum of earthquake magnitude 7 with epicentral distance 20 km is used as a design ground motion response spectrum (5 % damping target spectrum). The floor response spectra, obtained by the present method are compared to those

obtained by the time history method at each analytical stage. The power spectra at outcrop and at bedrock are shown in Fig.9 and Fig.10 respectively. A response power spectrum at the reactor building is shown in Fig.11 and the floor response spectrum is shown in Fig.12. In each figure, the PSD or the RS estimated by the time history analysis is obtained as the average of those obtained by 10 independent time history analyses. It can be seen in these figures that the PSDs and the FRs estimated by the present method consistently cover the results obtained by deterministic time history method with their 90% of confidence level.

CONCLUSION

An improved stochastic seismic response analysis method to estimate floor response spectra was improved, by taking correlation effect of successive peaks in a response time history into consideration in the conversion process between power spectrum and response spectrum. Floor response spectra estimated by the present method show good consistency for various damping ratios with the corresponding floor response spectra calculated by deterministic time history analyses.

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Fig.1
Comparison of Acceleration Response Spectrum Estimated by the Probabilistic Method with those Calculated by the Time History Method for Stationary Random Process. (10 % Damping)
10 Time Histories are used for the Time History Analysis.

Fig.2
Comparison of Acceleration Response Spectrum Estimated by the Probabilistic Method with those Calculated by the Time History Method for Stationary Random Process. (1 % Damping)
10 Time Histories are used for the Time History Analysis.

Fig.3 Acceleration Response Time Histories of One Degree of Freedom System of 5 Hz of Natural Frequency.

Fig.4 Correlation Function of the Response Time Histories Shown in Fig.3.

Fig.5 Expected Value for the Peak Factor as a Function of the Number of Peaks.

Fig.6 Comparison of Acceleration Response Spectrum Estimated by the Present Method with those Calculated by the Time History Method for Stationary Random Process. (10 % Damping Ratio) 10 Time Histories are used for the Time History Analysis.

Fig.7 Comparison of Acceleration Response Spectrum Estimated by the Present Method with those Calculated by the Time History Method for Stationary Random Process. (1 % Damping Ratio) 10 Time Histories are used for the Time History Analysis.

Fig. 8 Schematic Representation of Present Method

Fig. 9 Power Spectrum at the Outcrop

Fig. 10 Power Spectrum at the Bedrock

Fig. 11 Response Power Spectrum at Reactor Building

Fig. 12 Floor Response Spectrum at Reactor Building