Reduction of First Excursion Probability of Mechanical Systems
under Earthquake Excitations by Inelastic Restoring
Force-Deformation Relation*

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Important mechanical systems installed in nuclear power plants and other industrial facilities must be designed not to lose their performance during and after destructive earthquake excitations. In this paper, reduction of the first excursion probability of such mechanical systems with inelastic restoring force-deformation relation is examined. First, the first excursion probability of inelastic mechanical system is estimated from experiment using stationary random noises as input. Next, relation between restoring force and deformation is identified from simulation technique using hysteresis loop obtained from experiment. Next, effectiveness of reduction of the first excursion probability for mechanical systems subjected to earthquake excitation is examined by using nonstationary artificial time histories. Finally, obtained results are examined by theoretical technique using equivalent linearization method. It is concluded that the first excursion probability of inelastic mechanical system is smaller than that of elastic system.

Key Words : Vibration, First Excursion Probability, Ramberg-Osgood Restoring Force-Deformation Relation, Earthquake Excitation, Mechanical System

1. Introduction

The important mechanical systems such as mechanical equipment installed in the nuclear power plants and other industrial facilities should be designed not to lose their performance even if they are subjected to destructive earthquake excitations. It has been one of the important problems to estimate the failure probability of such important mechanical systems for assessment of seismic risk of nuclear power plants and other industrial facilities.^{1),2)} Authors have dealt with the first excursion failure among failure mechanisms of mechanical systems and have examined the estimation method for the first excursion probability. In the previous paper³⁾, considering the following two points; (1) design response spectrum are used for aseismic design of mechanical systems⁴⁾; (2) envelope functions which represent nonstationary characteristics of earthquake excitations have been proposed^{5),6)}, the authors have proposed an estimation method of the first excursion probability of mechanical systems subjected to nonstationary earthquake excitations compatible to the design spectrum and have examined the feature of the first excursion probability of mechanical systems. If a plastic deformation within allowable range is permitted at the supporting points of which

permanent deformations are not affect the mechanical system itself, it is expected that the first excursion probability will be reduced by energy absorbing effect. Considering this point, the authors have also shown quantitatively that the first excursion probability for a mechanical system with a perfectly-elasto-plastic restoring force-deformation relation can be reduced as compared with that for an elastic system.

In this paper, reduction of the first excursion probability with a general restoring force-deformation relation which is considered to be represented by hysteretic characteristics between elastic and perfectly-elasto-plastic is examined. First, from an experiment using a specimen with an inelastic hysteretic restoring force-deformation relation and using stationary white noise excitations as input, it is shown that the first excursion probability can be reduced as compared with that for an elastic system. Secondly, by a simulation method using a mechanical model with Ramberg-Osgood (R-O) restoring force-deformation relation which can represent a wide range of hysteretic characteristics from elastic to perfectly-elasto-plastic, it is found that R-O restoring force-deformation relation can be introduced to represent the restoring force-deformation relation of the specimen. Thirdly, by a simulation method using nonstationary artificial time histories, reduction of the first excursion probability of the mechanical system is examined for the case where the mechanical system is subjected to earthquake excitations. Finally, the results are examined by a theoretical method using the equivalent linearization method.

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2. Nomenclature

P_f	: first excursion probability of the mechanical system
h	: damping ratio of the mechanical system
ω_n	: natural circular frequency of the mechanical system
x	: absolute displacement of the mechanical system
y	: absolute displacement of the ground
z	: relative displacement of the mechanical system to the ground $=x-y$
z_g	: relative displacement of the ground to the base rock
h_g	: damping ratio of the ground model
ω_g	: predominant circular frequency of the ground model
$I(t)$	: envelope function which represents nonstationary characteristics of earthquake excitation
$G(\omega)$	: power spectral density function of the ground acceleration
G_0	: power spectral density function of the white noise which represents base rock motion
λ_A	: tolerance level with respect to absolute acceleration of mechanical system
λ_D	: tolerance level with respect to z
σ^2	: variance of variable described by subscript
κ	: covariance of variable described by subscript
F	: restoring force in the mechanical system
F_e	: yielding force
Z_e	: yielding displacement
C_e	: equivalent damping coefficient
ω_e	: equivalent natural circular frequency

3. Estimation of the First Excursion Probability by Experiment

The first excursion probability of the mechanical system is estimated by an experiment using a specimen with an inelastic hysteretic restoring force-deformation relation.

3.1 Experimental set-up

In order to estimate the first excursion probability P_f of the mechanical system with an inelastic hysteretic restoring force-deformation relation, subjected to stationary white noise excitations, the experimental set-up shown in Fig.1(a) is

(a) Experimental set-up (b) Specimen
Fig.1 Experimental set-up and specimen

used. ① is the specimen. A cantilever is used as the specimen. The size of the specimen is shown in Fig.1(b). Supporting part of the specimen is fixed by 4 bolts. ② is the supporting equipment of the specimen which is used to measure the relative displacement of the supporting part to the free edge of the specimen. It is designed to be rigid compared with the specimen. Aluminium is used as material of the specimen so that the natural frequency of the specimen is lower than that of the supporting equipment and the specimen is lighter than the supporting equipment. White noise excitations are generated by a random noise generator ③. The white noise signals are filtered by a band pass filter ④ in order to consider only the fundamental natural frequency of the specimen. The filtered signals are led to a shaker ⑤. An accelerometer ⑥ is used to measure the absolute acceleration of the free edge of the specimen. A noncontacting displacement meter ⑦ is used to measure the relative displacement of free edge of the specimen to the supporting part of the specimen. The measured acceleration and displacement time histories are digitized by AD converter ⑧. P_f is estimated by using these digitized time histories. Frequency response function of the specimen is determined by spectral analysis method⁷⁾ using the response time histories of the free edge of the specimen and that of the supporting part of the specimen subjected to stationary white noise excitation. From the determined frequency response function of the specimen, it is found that the fundamental natural frequency is 100Hz and damping ratio is 0.007, so the cut off frequencies for the band pass filter are chosen as 60Hz and 170Hz.

In the experiment, first, P_f for an elastic system is estimated in order to compare with that for system with an inelastic hysteretic restoring force-deformation relation. Next, P_f for an inelastic system is estimated by using the specimen with a crack near the supporting part ⑨.

3.2 Experimental results

The response time histories of the specimen are recorded for 50 stationary white noise excitations. The tolerance level for estimation P_f is determined by using the maximum value of 50 elastic system response time histories for the absolute acceleration, $\dot{x}_{\max}$, and the relative displacement, $z_{\max}$, as follows.

$$\lambda_A = d\dot{x}_{\max}, \lambda_D = dz_{\max} \quad (1)$$

where d is a constant. P_f is estimated by assuming that the failure of the mechanical system occurs at the instant when the absolute value of the response first reaches the tolerance level.

P_f for the absolute acceleration response is shown in Fig.2(a) and that for the relative displacement response is shown in Fig.2(b). Abscissa which represents time is normalized by the natural period of the specimen T_n . Solid lines in this figure are P_f for the inelastic system and dashed lines are that for the elastic system.

Fig.2 P_f estimated by experiment

From Fig.2, for absolute acceleration response, P_f for the inelastic system is seen to be considerably reduced as compared with that for the elastic system when d is greater than 0.3. For the relative displacement response, the degree of reduction of P_f is not greater than that for the absolute acceleration response. However, P_f for the inelastic system is considerably reduced as compared with P_f for the elastic system when d is greater than 0.3. From these results, it is found out that P_f can be reduced by the inelastic hysteretic restoring force-deformation relation.

4. Estimation of the First Excursion Probability by Simulation Method

Restoring force-deformation relation of the specimen is identified by a simulation method using a single-degree-of-freedom system with the same natural period and damping ratio as the specimen and with an inelastic restoring force-deformation relation. Using the identified system, experimental results are examined.

4.1 Identification of inelastic restoring force-deformation relation of the specimen

In order to fit an appropriate restoring force-deformation relation model to that of the specimen, the relation between restoring force and displacement of the specimen is obtained by using 100Hz sinusoidal excitation of which the frequency is equal to the natural frequency of the specimen. The result is shown in Fig.3. F and Z are normalized by F_s and Z_s , respectively, which are the maximum values of F and Z , respectively, for the sinusoidal excitation. It is considered that R-O restoring force deformation-relation which is shown in Fig. 4 fits the hysteresis loop shown in Fig.3. In Fig.4, AOB is referred to as the skeleton curve and BCA or ADB is a branch curve. These curves are described by the expres-

sions shown in Fig.4. When $\alpha=0$, the hysteresis loop corresponds to elastic system and when $r \rightarrow \infty$, it represents the perfectly-elasto-plastic restoring force-deformation relation. R-O hysteresis characteristics can represent a wide range of hysteresis loops from elastic to perfectly-elasto-plastic characteristics when α and r are varied⁸⁾. Three parameters α , r and F_e (or Z_e) must be determined for R-O hysteresis characteristics. Referring to the shape of hysteresis loop shown in Fig.3 and the data of the previous studies^{8),9)}, the best fit hysteresis loop of Fig.5 is obtained by using the least square method. Values of parameters for this hysteresis loop are $\alpha=0.1$, $r=7$ and $Z_e=0.4Z_{\max}$.

4.2 Estimation of the first excursion probability by simulation method

P_f estimated by using a single-degree-of-freedom system with hysteretic restoring force-deformation relation taking 50 stationary white noises as input is shown in Fig.6. Compared with Fig.2, P_f for $d=0.3$ for the inelastic system estimated by the simulation method is greater than that obtained by the experiment. However, P_f for the other values of d estimated by the simulation method is nearly equal to that

Fig.3 Restoring force-deformation relation obtained by experiment

Fig.4 R-O restoring force-deformation relation

Fig.5 R-O restoring force-deformation relation ($\alpha=0.1$, $r=7$, $Z_e=0.4Z_{\max}$)

Fig.6 P_f estimated by simulation method

obtained by the experiment. Therefore, it is valid to introduce R-O restoring force deformation relation to represent the hysteresis characteristics of the specimen. Since Z_e is equal to $0.4z_{\max}$, F_e is nearly equal to $0.4x_{\max}$. Therefore, when tolerance levels are greater than F_e or Z_e , P_f for the system with R-O restoring force-deformation relation can be reduced as compared with that for the elastic system.

5. Estimation of the First Excursion Probability Using Artificial Time Histories for Aseismic Design

In order to examine the validity of reduction of the first excursion probability of a mechanical system subjected to earthquake excitation, P_f is estimated by a simulation method using artificial time histories for aseismic design. Results are examined by the theoretical method.

5.1 Input earthquake excitation

Nonstationary artificial time histories compatible to design response spectrum are used as the input for the following reasons: design response spectra are used for actual aseismic design of structures⁴⁾; envelope functions which represent nonstationary characteristics of the earthquake excitations have been presented^{5), 6)}. Design response spectrum employed in this study is the standard response amplification factor of the first kind of the ground, which corresponds to the Tertiary Formation, for high pressure gas facilities established by the Japanese Ministry of International Trade and Industry⁴⁾. Envelope function used in this study is one for high pressure gas facilities¹⁰⁾ shown in Fig.7.

A representative value of damping ratio of mechanical system h is selected as 0.01 and natural period T_n is 0.3s. The value of $x_{\max}$ used for determining the tolerance level expressed by Eq(1) is obtained from

the design spectrum. $z_{\max}$ is obtained by dividing $x_{\max}$ by ω_n^2 . When T_n is 0.3s, $x_{\max} = 4.65$ and $z_{\max} = 0.0106 \text{ cm/gal}^{11), which are normalized by the maximum ground acceleration. The values for α , r and Z_e used to determine R-O restoring force-deformation relation are the same as those obtained from the experiment.$

Fig.7 Envelope function

5.2 Estimated results for the first excursion probability by simulation method

P_f obtained by using 50 artificial time histories is shown in Fig.8. Fig.8(a) shows P_f for the absolute acceleration response and Fig.8(b) shows P_f for the relative displacement response. For the absolute acceleration response, when $d=0.4$, P_f for the system with R-O restoring force-deformation relation is smaller than that for the elastic system. When d is greater than 0.4, P_f is significantly reduced for the inelastic system. For the relative displacement response, the reduction of P_f is not so significant as that of the absolute acceleration response. However, when d is greater than 0.4, P_f for the system with R-O restoring force-deformation relation is smaller than that for the elastic

(a) P_f for absolute acceleration response (b) P_f for relative displacement responseFig.8 P_f estimated by simulation method ($h=0.01$, $T_n=0.3\text{s}$, $\alpha=0.1$, $r=7$, $Z_e=0.4z_{\max}$)

system. Therefore, when the tolerance level is greater than F_e or Z_e , P_f for the system with R-O restoring force-deformation relation is smaller than that for the elastic system. Especially, P_f is significantly reduced for the absolute acceleration response.

Next, it is important that a mechanical system should be designed not to lose its performance after the earthquake excitation, so P_f is estimated when enough time has passed after the main shock. For the same values of d , P_f for the relative displacement response is greater than that for the absolute acceleration response. Attention was focused on P_f for the relative displacement response.

In Fig. 9, P_f estimated for different T_n is shown taking d as abscissa. From this figure, P_f estimated when enough time has passed after the main shock is practically independent of T_n .

Next, in order to examine the effect of Z_e , P_f estimated when enough time has passed after the main shock is estimated for different values of Z_e expressed as Eq.(2).

$$Z_e = \delta z_{\max} \quad (2)$$

The estimated P_f is shown in Fig. 10. Since the maximum value of z for the elastic system is equal to $z_{\max}$ for each artificial time history, P_f for the elastic system is about 100% when d is less than unity. However, P_f for the system with R-O restoring force-deformation relation is smaller than 100% for the tolerance level

Fig. 9 P_f estimated when enough time has passed after the main shock ($h=0.01$, $\alpha=0.1$, $r=7$, $Z_e=0.4z_{\max}$)

Fig. 10 P_f estimated when enough time has passed after the main shock ($h=0.01$, $T_n=0.3s$, $\alpha=0.1$, $r=7$)

greater than Z_e . P_f decreases as Z_e decreases. When $\delta=0.7$ and $\delta=0.3$, if displacement greater than $z_{\max}$ and $0.8z_{\max}$, respectively, is permitted, P_f is about zero.

5.3 Estimation of the first excursion probability by theoretical method

P_f for the relative displacement response is estimated by application of the theoretical method presented in the previous paper³⁾ which has been developed for a system with perfectly-elasto-plastic restoring force-deformation relation.

5.3.1 Theoretical equation for estimation of the first excursion probability

Theoretical equation for estimation of P_f is given as follows.

$$P_f(t) = 1 - \exp\left\{-2 \int_0^t v(t) dt\right\} \quad (3)$$

Assuming that the distribution of $z(t)$ is the normal distribution and instants at which $z(t)$ crosses λ_D are statistically independent, $v(t)$ is given as

$$v(t) = \frac{1}{2\pi} \frac{\sqrt{D}}{\sigma_z^2} \left[\exp\left\{-\frac{\lambda_D^2}{2\sigma_z^2} \left(1 + \frac{\kappa^2 \lambda_D^2}{D}\right)\right\} + \lambda_D \kappa \sqrt{\frac{\pi}{2D\sigma_z^2}} \exp\left\{-\frac{\lambda_D^2}{2\sigma_z^2}\right\} (1 + \operatorname{erf}(C)) \right] \quad (4)$$

where

$$C = \frac{\kappa \lambda_D \lambda_0}{\sqrt{2D\sigma_z^2}}, \quad D = \sigma_z^2 \sigma_z^2 - \kappa^2 \lambda_D^2$$

$$\operatorname{erf}(u) = \frac{2}{\sqrt{\pi}} \int_0^u e^{-y^2} dy$$

Since $G(\omega)$ can be approximately expressed by Tajimi's equation¹²⁾ as follows, a mechanical model of the ground can be simulated by a single-degree-of-freedom system³⁾.

$$G(\omega) = \frac{(2h_g \omega_g \omega)^2 + \omega_g^4}{(\omega_g^2 - \omega^2)^2 + (2h_g \omega_g \omega)^2} G_0 \quad (5)$$

The expected value of $G(\omega)$ is estimated by using 50 artificial time histories. Using the least square method, the following values of the parameters are obtained. $h_g = 0.5$, $T_g (=2\pi/\omega_g) = 0.285s$ and $G_0 = 1.7 \times 10^{-3} (1/g^2)$. When the power spectral density function of the ground motion can be expressed as Eq. (5), the Fokker-Planck equation for P with respect to $z, \dot{z}, z_g$ and $\dot{z}_g$ is obtained as follows.

$$\begin{aligned} \frac{\partial P}{\partial t} = & -\frac{\partial P}{\partial z} \dot{z} + 2h\omega_n \dot{p} - \frac{\partial P}{\partial \dot{z}} \\ & \times \{-2h\omega_n \dot{z} - F + I(t)(2h\omega_g \dot{z}_g + \omega_g^2 z_g)\dot{p}\} \\ & - \frac{\partial P}{\partial z_g} \dot{z}_g + 2h\omega_g \dot{p} + \frac{\partial P}{\partial \dot{z}_g} (2h\omega_g \dot{z}_g + \omega_g^2 z_g) \\ & + \frac{\partial^2 P}{\partial \dot{z}^2} \frac{\pi G_0}{2} \end{aligned} \quad (6)$$

F for the system with R-O restoring force-deformation relation is equivalently linearized as follows.

$$F = C_e \dot{z} + \omega_e^2 z \quad (7)$$

When the yielding effect is not so great, it is assumed that the response of restoring force produces a yielding force after the response increases and it approaches the stationary random process. Since the

value of h is relatively small, $z(t)$ is a narrow band random process and the distribution of amplitudes of $z(t)$ can be approximately expressed as Rayleigh distribution. C_e and ω_e are obtained from the stationary random theory as follows.

$$\left. \begin{aligned} C_e &= \int_0^\infty \frac{4\alpha Z_e F_e}{\pi \omega_e z^2} \frac{r-1}{r+1} \left(\frac{F}{F_e} \right)^{r-1} \frac{z}{\sigma_z^2} \\ &\quad \times \exp\left(-\frac{z^2}{2\sigma_z^2}\right) dz \\ \omega_e^2 &= \int_0^\infty \frac{F}{z} \frac{z}{\sigma_z^2} \exp\left(-\frac{z^2}{2\sigma_z^2}\right) dz \end{aligned} \right\} \quad (8)$$

The second moments with respect to z and $\dot{z}$ are to be obtained to estimate P_f by using Eq.(4). Applying integration by parts to Eq.(6), the momentum equations with respect to the second moments are obtained as follows.

$$\left. \begin{aligned} \frac{\partial \sigma_z^2}{\partial t} &= 2K z \dot{z} \\ \frac{\partial \sigma_{\dot{z}}^2}{\partial t} &= -2\sigma_z^2 - 2K z \dot{z} \\ &\quad + 2I(t)(2h_g \omega_g K z \dot{z} + \omega_g^2 K z \dot{z}) \\ \frac{\partial \sigma_{z\dot{z}}}{\partial t} &= 2K z \dot{z} \\ \frac{\partial \sigma_{\dot{z}z}}{\partial t} &= -4h_g \omega_g \sigma_z^2 - 2\omega_g^2 K z \dot{z} - \pi G_0 \\ \frac{\partial K z \dot{z}}{\partial t} &= \sigma_z^2 - H K z \dot{z} \\ &\quad - \omega_e^2 \sigma_z^2 + I(t)(2h_g \omega_g K z \dot{z} + \omega_g^2 K z \dot{z}) \\ \frac{\partial K z \dot{z}}{\partial t} &= K z \dot{z} + K z \dot{z} \\ \frac{\partial K z \dot{z}}{\partial t} &= K z \dot{z} - 2h_g \omega_g K z \dot{z} - \omega_g^2 K z \dot{z} \\ \frac{\partial K z \dot{z}}{\partial t} &= -H K z \dot{z} - \omega_e^2 K z \dot{z} \\ &\quad + I(t)(2h_g \omega_g K z \dot{z} + \omega_g^2 K z \dot{z}) + K z \dot{z} \\ \frac{\partial K z \dot{z}}{\partial t} &= -H K z \dot{z} - \omega_e^2 K z \dot{z} \\ &\quad + I(t)(2h_g \omega_g \sigma_z^2 + \omega_g^2 K z \dot{z}) \\ &\quad - 2h_g \omega_g K z \dot{z} - \omega_g^2 K z \dot{z} \\ \frac{\partial K z \dot{z}}{\partial t} &= \sigma_z^2 - 2h_g \omega_g K z \dot{z} - \omega_g^2 \sigma_z^2 \end{aligned} \right\} \quad (9)$$

where $H = 2h\omega_n + C_e$.

P_f is estimated by solving Eq.(9) and using Eq.(4) and Eq.(3).

5.3.2 Estimation results of the first excursion probability

P_f estimated by using the above mentioned method is shown in Fig.11. This figure corresponds to Fig.8. Comparing Fig.11 with Fig.8(b), P_f estimated by the theoretical method is found to be greater

Fig.11 P_f estimated by theoretical method ($h=0.01$, $T_n=0.3s$, $\alpha=0.1$, $r=7$, $Z_e=0.4z_{max}$)

than that by the simulation method. The reason is that $z(t)$ is a narrow band random process, so strictly speaking, the assumption that instants at which $z(t)$ crosses λ_D are statistically independent is not appropriate. However, for the tolerance level which is greater than Z_e , the feature can be seen that P_f for a mechanical system with R-O restoring force-deformation relation is smaller than that for an elastic system. Therefore, qualitative characteristics of P_f can be obtained by the proposed theoretical method. This theoretical method is found to give a conservative estimate of P_f .

6. Conclusions

Reduction of the first excursion probability is examined by adopting an inelastic restoring force-deformation relation. The obtained results are summarized as follows.

- (1) From experiment using a specimen subjected to stationary white noise excitations, it can be seen that the first excursion probability P_f for the system with an inelastic restoring force-deformation relation is smaller than that for an elastic system.
- (2) P_f is estimated by a simulation method using a mechanical model with R-O restoring force-deformation relation which can describe a wide range of hysteretic characteristics from elastic to perfectly-elasto-plastic. The obtained P_f is close to that determined by the experiment, so it is found that R-O hysteretic characteristics can be reasonably introduced for the restoring force-deformation relation of the specimen.
- (3) In order to examine the validity of reduction of P_f obtained by the experiment, P_f is estimated by a simulation method using nonstationary artificial time histories compatible to the design response spectrum. From this simulation, it can be seen that P_f for the system with R-O restoring force-deformation relation is smaller than that for the elastic system for the tolerance level greater than the yielding force F_e or the yielding displacement Z_e .
- (4) P_f at the time when enough time has passed after main shock is not so dependent on the natural period of mechanical system, T_n , for the same tolerance level. P_f decreases as Z_e decreases.
- (5) Qualitative feature of P_f can be obtained by the theoretical method using the equivalent linearization method. This theoretical method gives a conservative estimate of P_f .

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