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Generate floor response spectra, Part 2: Response spectra for equipment-structure resonance

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HIGHLIGHTS

- The concept of tRS is proposed to deal with tuning of equipment and structures.
- Established statistical approaches for estimating tRS corresponding to given GRS.
- Derived a new modal combination rule from the theory of random vibration.
- Developed efficient and accurate direct method for generating floor response spectra.

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ABSTRACT

When generating floor response spectra (FRS) using the direct spectra-to-spectra method developed in the companion paper, probability distribution of t-response spectrum (tRS), which deals with equipment-structure resonance or tuning, corresponding to a specified ground response spectrum (GRS) is required.

In this paper, simulation results using a large number of horizontal and vertical ground motions are employed to establish statistical relationships between tRS and GRS. It is observed that the influence of site conditions on horizontal statistical relationships is negligible, whereas the effect of site conditions on vertical statistical relationships cannot be ignored. Considering the influence of site conditions, horizontal statistical relationship suitable for all site conditions and vertical statistical relationships suitable for hard sites and soft sites, respectively, are established. The horizontal and vertical statistical relationships are suitable to estimate tRS for design spectra in USNRC R.G. 1.60 and NUREG/CR-0098, Uniform Hazard Spectra (UHS) in Western North America (WNA), or any GRS falling inside the valid coverage of the statistical relationship.

For UHS with significant high frequency spectral accelerations, such as UHS in Central and Eastern North America (CENA), an amplification ratio method is proposed to estimate tRS.

Numerical examples demonstrate that the statistical relationships and the amplification ratio method are acceptable to estimate tRS for given GRS and to generate FRS using the direct method in different practical situations.

1. Introduction

In seismic design, qualification, and evaluation of critical engineering structures, such as nuclear power plants, it is crucial to determine floor response spectra (FRS) at various floors where important systems, structures, and components (SSC) performing operational and safety-related functions are mounted. Seismic inputs are usually specified in terms of ground response spectra (GRS) defined as

$$\mathcal{S}_{\mathrm{A}}(\omega,\zeta)=|\omega \mathrm{e}^{-\zeta\omega t}\sin\omega t * \ddot{u}_{\mathrm{g}}(t)|_{\max}, \tag{1}$$

where $\ddot{u}_{\mathrm{g}}(t)$ is the ground acceleration, ω and ζ are the circular natural frequency and damping ratio of a single degree-of-freedom (SDOF) oscillator mounted on the ground.

When the direct spectra-to-spectra method, developed in the companion paper “Generate Floor Response Spectra, Part 1: Direct Spectra-to-Spectra Method”, is applied to generate FRS, t-response spectrum (tRS) defined by

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$$\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}(\omega,\zeta)=\frac{1}{2}\left|-\omega^{2}te^{-\zeta\omega t}\cos\omega t*\ddot{u}_{\mathrm{g}}(t)+\omega e^{-\zeta\omega t}\sin\omega t*\ddot{u}_{\mathrm{g}}(t)\right|_{\max} \tag{2}$$

corresponding to a given GRS is required when the equipment and the supporting structure are in resonance (tuning). Due to the presence of a time variable t in the first convolution term, it is difficult to obtain an analytical expression for Eq. (2) in terms of GRS.

In this paper, statistical relationships between tRS and GRS are established through regression of simulation results using a large number of ground motions. In Section 2, the ground motion selection criteria are discussed; different suites of ground motions recorded with different site conditions are selected. In Section 3, horizontal and vertical statistical relationships between tRS and GRS are established, respectively, using different suites of horizontal and vertical ground motions. The horizontal and vertical statistical relationships are suitable for estimating tRS for GRS falling inside the valid coverage of the statistical relationships. If a GRS falls outside the valid coverage of the statistical relationships, an amplification ratio method is proposed to estimate tRS. In Section 4, numerical examples are presented to demonstrate the efficiency and accuracy of the approaches in estimating tRS. Some conclusions are drawn in Section 5.

The novel and significant contribution of this paper is to develop accurate statistical approaches for estimating tRS corresponding to given GRS, which can be used in generating FRS efficiently and accurately.

2. Ground motion selection

To determine statistical relationships between tRS and GRS, a large number of ground motions are required. In this study, ground motions recorded with different site conditions are selected by the following selection criteria:

1. Ground motions with complete information, including three components (two horizontal components and one vertical component) and site classifications are considered. For one set of tri-directional ground motions, characteristics of the two horizontal ground motions are similar. Therefore, only one horizontal component randomly selected from the two horizontal components is used to establish the horizontal statistical relationship between tRS and GRS, and the corresponding vertical component is used to establish the vertical statistical relationship.
2. Since the frequency range from 0.3 Hz to 24 Hz is important for structures and components of nuclear power facilities (USNRC, 2007), power spectral density (PSD) of selected ground motions should be sufficiently high in this frequency range to prevent a deficiency of power over this significant frequency band.
3. Pulse-like ground motions are usually observed in near-seismic-source fields with directivity focusing or fling effects. They are significantly affected by rupture mechanism, and very different from ordinary ground motions. Comparing with ordinary ground motions, pulse-like ground motions possess long periods and large amplitudes, unusual response spectral shapes, and concentration of energy in one or very few pulses. Nuclear power plant sites are usually not close to seismic sources. Therefore, pulse-like ground motions are excluded.

Following these selection criteria, 49 horizontal and 49 vertical ground motions recorded at B sites, 154 horizontal and 154 vertical ground motions recorded at C sites, and 220 horizontal and 220 vertical ground motions recorded at D sites are selected from the PEER strong motion database and the European strong-motion database (Ambraseys et al., 2002). The site categories B, C, and D follow the National Earthquake Hazard Reduction Program (NEHRP) site classification criteria (ASCE, 2010; IBC, 2012).

3. Statistical relationships between tRS and GRS

In this section, statistical relationships between tRS and GRS are established based on ground motions recorded on different types of sites, including the 28 horizontal ground motions and 14 vertical ground motions used by Newmark and Hall to construct design spectra in NUREG/CR-0098 (Newmark and Hall, 1978), 98, 308, and 440 ground motions recorded at B, C, and D sites, respectively.

Regression analysis is a statistical method that establishes a statistical relationship between a dependent variable (response variable) and one or more independent variables (predictor variables). To construct the statistical relationship between tRS and GRS, tRS and GRS of the selected ground motions are calculated first; tRS $\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}(f,\zeta)$ and GRS $\mathcal{S}_{\mathrm{A}}(f,\zeta)$ are used as the response variable and the predictor variable, respectively. The regression model or the statistical relationship, is determined after evaluating the random relationship between $\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}(f,\zeta)$ and $\mathcal{S}_{\mathrm{A}}(f,\zeta)$. Suppose the regression model is of the form

$$\ln\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}(f,\zeta)=c_1(\zeta,f)+c_2(\zeta,f)\cdot\ln\mathcal{S}_{\mathrm{A}}(f,\zeta)+\varepsilon\sigma_{\ln\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}}, \tag{3}$$

where $c_1(\zeta,f)$ and $c_2(\zeta,f)$ are coefficients of regression, ε is the number of standard deviations of a single predicted value of $\ln\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}(f,\zeta)$ deviating from the mean value of $\ln\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}(f,\zeta)$, and $\sigma_{\ln\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}}$ is the standard deviation.

In practice, for a given GRS $\mathcal{S}_{\mathrm{A}}(\zeta,f)$, with or without a prescribed non-exceedance probability (NEP), tRS at each frequency is modelled using *lognormal distribution*. tRS $\mathcal{S}_{\mathrm{A}}^{\mathrm{t},p}(\zeta,f)$ with any NEP p corresponding to the given GRS can be estimated as:

$$\ln\mathcal{S}_{\mathrm{A}}^{\mathrm{t},p}(\zeta,f)=c_1(\zeta,f)+c_2(\zeta,f)\cdot\ln\mathcal{S}_{\mathrm{A}}(\zeta,f)+\sigma_{\ln\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}}(\zeta,f)\cdot\Phi^{-1}(p). \tag{4}$$

In this section, the detailed procedure to determine the coefficients of regression $c_1(\zeta,f)$ and $c_2(\zeta,f)$, and the standard deviation $\sigma_{\ln\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}}(\zeta,f)$ is presented. The results are summarized in Table 2 and Tables 5 and 6, respectively, for horizontal motions and vertical motions; for frequencies not listed in these tables, the coefficients and standard deviations can be obtained using linear interpolation in the logarithmic scale of frequencies.

3.1. Procedure to establish statistical relationships between tRS and GRS

The procedure to establish the statistical relationship is as follows:

Step 1. All selected ground motions in a suite are scaled to a constant PGA, e.g., PGA = 0.3 g.

Step 2. For a fixed damping ratio ζ, calculate GRS $\mathcal{S}_{\mathrm{A}}(f,\zeta)$ and tRS $\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}(f,\zeta)$ for frequencies f uniformly spaced over the logarithmic scale of a required frequency range, e.g., from 0.1 to 100 Hz.

Step 3. Calculate amplification ratios

$$AR(f,\zeta)=\frac{\mathcal{S}_{\mathrm{A}}^{\mathrm{t}}(f,\zeta)}{\mathcal{S}_{\mathrm{A}}(f,\zeta)}, \tag{5}$$

for all ground motions in the suite, and determine the median $AR_{50\%}$ and $AR_{84.1\%}$ with 50% and 84.1% NEP, respectively.

Step 4. Analyze the trend of the median amplification ratios $AR_{50\%}$.

Two examples are shown in Figs. 1 and 2 to illustrate the trend of the amplification ratio AR for 5% damping ratios.