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A scaling method for generating floor response spectra

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ABSTRACT

Efficient and accurate determination of Floor Response Spectra (FRS) is critical in seismic risk analysis and design. Scaling methods, which allow the generation of FRS corresponding to new Ground Response Spectra (GRS) by multiplying existing FRS with appropriate scaling factors rather than by performing re-analyses of the structure, are efficient and economical approaches. However, in many practical situations, it is challenging to generate FRS not only by scaling but also by analyzing structural responses due to the lack of structural model information.

A recent breakthrough in generating FRS using a direct spectra-to-spectra method prompted the development of the scaling method presented in this paper. The analytical formulation of the direct method provides a strong physical insight into the essential characteristics of FRS, which allows the identification of dynamical information of significant equivalent modes of the underlying structure from the available FRS and GRS. Scaling factors are then determined in terms of the dynamical information (modal frequencies, modal damping ratios, and modal contribution factors) and input GRS. Numerical examples of a typical service building in nuclear power plants show that the FRS obtained by this scaling method agree very well with the results obtained from a large number of time history analyses. It is also demonstrated that this method provides accurate FRS for various damping ratios when the interpolation methods recommended in the current standards are not applicable. The proposed method, which is efficient, accurate, and convenient to implement, allows engineers to use as much of the available results of previous analyses as possible without performing a complete dynamic analysis, which is time consuming and introduces extra costs.

1. Introduction

Floor Response Spectra (FRS), also called In-structure Response Spectra (IRS) in some standards and literature, are commonly used as input in seismic evaluation for Systems, Structures, and Components (SSCs) in nuclear power plants. Efficient and accurate determination of FRS is critical in seismic risk analysis and design of nuclear power plants. In many practical situations, scaling methods are efficient and economical approaches to obtain FRS:

Scaling Problem 1: Knowing FRS $\mathcal{S}_{\rm F}(f,\zeta_0)$ with one or only a few values of equipment damping ratio, it is required to determine $\mathcal{S}_{\rm F}(f,\zeta_0')$ for a number of different equipment damping ratios ζ_0'.

Scaling Problem 2: Knowing FRS-I $\mathcal{S}_{\rm F\text{-}I}(f,\zeta_0)$ with one or only a few values of equipment damping ratio for Ground Response Spectra (GRS-I) $\mathcal{S}_{\rm G\text{-}I}(f,\zeta)$, it is required to determine FRS-II $\mathcal{S}_{\rm F\text{-}II}(f,\zeta_0')$ for a number of different equipment damping ratios ζ_0' under different GRS-II $\mathcal{S}_{\rm G\text{-}II}(f,\zeta)$.

In the following, some existing solutions for both scaling problems are reviewed briefly. The importance and challenges of scaling methods are highlighted.

Scaling Problem 1

Scaling Problem 1 arises quite frequently in practice. Usually FRS corresponding to one or only a few damping ratios are available. However, FRS for various damping ratios, which may range from 2% to 15%, are required.

For example, for many existing nuclear power plants, usually low structural damping ratios were used in the original dynamic models. Also the final FRS curves were presented with low equipment damping ratios up to 5% or 7%. In seismic fragility analysis,

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median damping ratios for structures are required, which may be larger than those used in the original dynamic analyses; FRS with higher equipment damping ratios may also be required. Engineering activities, driven by schedule and budget, could call for a prompt and economical approach to generate the updated FRS for high equipment damping ratios with the high structural damping ratios.

ASCE 4-98 Clause 2.2.1 (ASCE, 1998) provides the following equation to determine $\mathcal{S}_F(f,\zeta)$ from $\mathcal{S}_F(f,\zeta_1)$ and $\mathcal{S}_F(f,\zeta_2)$:

$$\mathcal{S}_F(f,\zeta)=\mathcal{S}_F(f,\zeta_1)+[\mathcal{S}_F(f,\zeta_2)-\mathcal{S}_F(f,\zeta)]\frac{\ln\zeta-\ln\zeta_1}{\ln\zeta_2-\ln\zeta_1}, \tag{1.1}$$

which can be written as

$$\frac{\mathcal{S}_F(f,\zeta)-\mathcal{S}_F(f,\zeta_1)}{\mathcal{S}_F(f,\zeta_2)-\mathcal{S}_F(f,\zeta_1)}=\frac{\ln\zeta-\ln\zeta_1}{\ln\zeta_2-\ln\zeta_1}, \tag{1.2}$$

i.e., $\mathcal{S}_F(f,\zeta)$ is determined by linear interpolation in the $\mathcal{S}_F(f,\zeta)$-$\ln\zeta$ plane.

ASCE 4-98 Clause 3.4.2.4 (ASCE, 1998) gives the following equation

$$\mathcal{S}_F(f,\zeta)=\sqrt{\mathcal{S}_F^2(f,\zeta_2)+[\mathcal{S}_F^2(f,\zeta_1)-\mathcal{S}_F^2(f,\zeta_2)]\frac{\zeta_1}{\zeta}\left(\frac{\zeta-\zeta_2}{\zeta_1-\zeta_2}\right)},\quad \text{for } \zeta_1<\zeta<\zeta_2\leq 3\zeta_1. \tag{1.3}$$

Eq. (1.3) can be written as

$$\frac{\mathcal{S}_F^2(f,\zeta_2)-\mathcal{S}_F^2(f,\zeta)}{\zeta_2-\zeta}=\frac{\zeta_1}{\zeta}\,\frac{\mathcal{S}_F^2(f,\zeta_2)-\mathcal{S}_F^2(f,\zeta_1)}{\zeta_2-\zeta_1}. \tag{1.4}$$

Note that

$$\frac{\mathcal{S}_F^2(f,\zeta_2)-\mathcal{S}_F^2(f,\zeta)}{\zeta_2-\zeta}=\frac{\mathcal{S}_F^2(f,\zeta_2)-\mathcal{S}_F^2(f,\zeta_1)}{\zeta_2-\zeta_1} \tag{1.5}$$

amounts to determining $\mathcal{S}_F^2(f,\zeta)$ by linear interpolation in the $\mathcal{S}_F^2(f,\zeta)$-ζ plane. Since $\zeta_1/\zeta<1$, the slope of the solid line given by Eq. (1.4) is less than the slope of the dashed line given by linear interpolation (1.5), as illustrated in Fig. 1. FRS determined from Eq. (1.4) are more conservative than the results given by linear interpolation in the $\mathcal{S}_F^2(f,\zeta)$-ζ plane.

SQUG GIP Section 4.2.2 (SQUG, 2001) provides two results for FRS:

1. For FRS shape similar to the Bounding Spectrum (without very narrow peaks),

$$\mathcal{S}_F(f,\zeta)=\mathcal{S}_F(f,\zeta_0)\sqrt{\frac{\zeta_0}{\zeta}}\ \Rightarrow\ \mathcal{S}_F(f,\zeta)\sim\frac{1}{\sqrt{\zeta}}. \tag{1.6}$$

For all $f>f_{\text{Peak}}$ (corresponding to peak of FRS), $\mathcal{S}_F(f,\zeta)\geqslant$ ZPA (zero-period acceleration). Eq. (1.6) amounts to scaling $\mathcal{S}_F(f,\zeta)$ proportional to $1/\sqrt{\zeta}$.

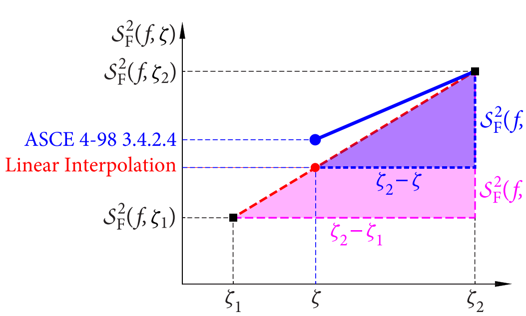

Fig. 1. Scaling method for FRS given by ASCE 4-98 Clause 3.4.2.4.

2. For equipment mounted below about 40 feet above the effective grade and has a fundamental natural frequency greater than about 8 Hz,
   - $f\leqslant 8$ Hz: $\mathcal{S}_F(f,\zeta)=\mathcal{S}_F(f,\zeta_0)\sqrt{\frac{\zeta_0}{\zeta}}\ \Rightarrow\ \mathcal{S}_F(f,\zeta)\sim\frac{1}{\sqrt{\zeta}}$;
   - $f\geqslant 20$ Hz: $\mathcal{S}_F(f,\zeta)=\mathcal{S}_F(f,\zeta_0)$, i.e. assuming that damping has no effect;
   - 8Hz $<f<$ 20Hz: $\frac{\log\mathcal{S}_F(f,\zeta)-\log\mathcal{S}_F(8\text{Hz},\zeta)}{\log f-\log 8}=\frac{\log\mathcal{S}_F(20\text{Hz},\zeta)-\log\mathcal{S}_F(8\text{Hz},\zeta)}{\log 20-\log 8}$, i.e., $\mathcal{S}_F(f,\zeta)$ is obtained from linear interpolation in $\log\mathcal{S}_F(f,\zeta)$-$\log f$ plane between 8 Hz and 20 Hz.

From this summary, it is clearly seen that existing scaling approaches are essentially.

- a simple scaling, such as Eq. (1.6) with a uniform scaling factor for all frequency f; or
- linear interpolation based on various assumptions between $\mathcal{S}_F(f,\zeta)$ and ζ or f. The methods are not valid for extrapolation, or when only one FRS with one equipment damping ratio is available.

Scaling Problem 2

An accurate and reliable method for Scaling Problem 2 is important in many engineering projects. For example, in a life-extension project of an existing nuclear power plant, $\mathcal{S}_F i(f,\zeta)$ are usually available for Design Basis Earthquake (DBE) $\mathcal{S}_{G\text{-I}}(f,\zeta)$. $\mathcal{S}_{F\text{-II}}(f,\zeta)$ are required for site-specific ground motion response spectra (GMRS) or review-level earthquakes (RLE) $\mathcal{S}_{G\text{-II}}(f,\zeta)$ in seismic margin assessment or probabilistic safety assessment. Project scope and budget may not warrant a complete seismic structural analysis to obtain $\mathcal{S}_{F\text{-II}}(f,\zeta)$.

In rehabilitation projects, sometimes structures need to be strengthened due to a higher seismicity $\mathcal{S}_{G\text{-II}}(f,\zeta)$ than the original design $\mathcal{S}_{G\text{-I}}(f,\zeta)$. It is tricky to decide which strengthen scheme is the most economical from the seismic point of view. A quick yet accurate approach to determine $\mathcal{S}_{F\text{-II}}(f,\zeta)$ from $\mathcal{S}_{G\text{-II}}(f,\zeta)$ will assist engineers to decide which strengthen scheme is optimal.

Similarly, in a new-build, $\mathcal{S}_{F\text{-I}}(f,\zeta)$ are available for a generic design based on a standard GRS $\mathcal{S}_{G\text{-I}}(f,\zeta)$, such as those in CSA N289.3 (CSA, 2010) or USNRC R.G. 1.60 (USNRC, 2014). An efficient and good estimate of $\mathcal{S}_{F\text{-II}}(f,\zeta)$ for site-specific GRS $\mathcal{S}_{G\text{-II}}(f,\zeta)$ is critical for feasibility analysis, budgeting, scheduling, bidding and tendering, and procurement of important equipment, which may take years to manufacture, before the site-specific design is finalized and a complete seismic analysis is performed.

It is obviously desirable for engineers to use as much of the available information and results of previous analyses as possible without performing a complete dynamic analysis, which is time consuming and introduces extra costs. However, the existing scaling methods recommended in EPRI NP-6041-SL (EPRI, 1991) basically give approximate estimates with an uniform scaling factor and are restricted to some special cases. Because of their crude approximations, they are not widely used in nuclear industry.

Objective and scope

The primary challenges and difficulties in developing FRS based on results of previous analyses include:

1. Related to Scaling Problem 1, FRS with various equipment damping ratios, which may range from 2% to 15%, are required when FRS corresponding to only a few damping ratios (e.g., 5%) are available.
2. Differences in the spectral shapes between GRS-I of the previous analysis and the new GRS-II may result in significant variations in the FRS shapes.