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Uniformly Probable Coupled Response Spectra for Secondary Systems

Andréia Diniz Almeida.[1], João Luis Roehl [1]

[1] PUC-Rio -Pontifícia Universidade Católica do Rio de Janeiro, Brazil

ABSTRACT

In the seismic analysis of secondary system structures the common practice is to use a spectral modal solution; in this analysis, the design spectrum is obtained from the acceleration time-history of the primary structure nodes which support the secondary system when the primary system is excited at its base by the design ground motion. This practice has been criticized in several aspects including because it does not take into account the dynamical property interaction of the two systems. The situation is further criticizable if one considers the highly random character of the excitation and the large number of the secondary structures to be analyzed with variable characteristics and diversified behavior. One presents now a new intent on the direction to a more general procedure to obtain these secondary system design response spectra. This procedure allows one to take into account the main interaction effects of the dual-system dynamical properties, as well as to reach to a design response spectrum which has all over its main frequency region an eligible equal probability of not to be exceeded.

KEY WORDS: secondary system, coupled response, uniform probable response spectrum.

INTRODUCTION

In the seismic analysis of secondary system structures the common practice is to use a spectral modal solution; in this analysis, the design spectrum is obtained from the acceleration time-history of the primary structure nodes which support the secondary system when the primary system is excited at its base by the design ground motion. This practice has been criticized in several aspects including because it does not take into account the dynamical property interaction of the two systems [1,2,3,4].

The situation is further criticizable if one considers the highly random character of the excitation and the large number of the secondary structures to be analyzed with variable characteristics and diversified behavior. Some of these concerns have received very good attention and treatment from researchers on the area [1,2,5,6].

One presents now a new intent on the direction to a more general procedure to obtain these secondary system design response spectra and uses for this purpose the following resources:

- consideration of the ground excitation at the site defined by a prescribed power spectrum density function – $PSDF_0$;
- transference of this prescribed $PSDF_0$ across the primary system to a single degree of freedom model of the secondary system (SS), conveniently attached to the primary system (PS), to obtain the PSDF of the coupled response of the secondary system;
- development of a first passage analysis [7] to produce a uniformly probable coupled response spectrum (UPCRS) for the secondary system [8].

This procedure allows one to take into account the main interaction effects of the dual-system dynamical properties, as well as to reach to a design response spectrum which has all over its main frequency region an eligible equal probability to envelop the response spectrum generated by any accelerogram pertaining to the time function family defined by the prescribed $PSDF_0$. The analysis is carried in the frequency domain using the same model as for the primary structure itself including all the refinements as, for instance, the soil structure interaction.

A series of examples having a nuclear power plant reactor building as the primary structure illustrates the application of the procedure and its advantages when one compares with the common design practice.

METHODOLOGY

First, assumes the site sismicity to be defined by a one-sided acceleration power spectral density function, PSD.

The coupled analysis is performed by conveniently connecting a single degree of freedom (SDOF) system, representing the secondary system, to the primary system region where the coupled response spectrum is to be determined. One follows by considering the sample space of the secondary system weakly stationary response when the primary structure is subjected at its base to the accelerograms family which may attend exactly to the power spectral density function, $PSDF_0$. This response is defined by the also one-sided acceleration power spectral density function, $PSDF_{AA}$:

$$PSDF_{AA}(\omega) = \left|\mathrm{H}(\omega)\right|^2 \cdot PSDF_0 \tag{1}$$

where, H(w) is the acceleration transfer function from the excitation control point to the SS control node.

One further considers the first passage problem equation, according to Vanmarcke [7], to establish the response probability distribution function not to exceed a response level ***a***, given by:

$$F(a) = \left(1 - e^{\frac{-a^2}{2\cdot\lambda_0}}\right) \cdot \exp\left(-\alpha \cdot t^*\right) \tag{2.a}$$

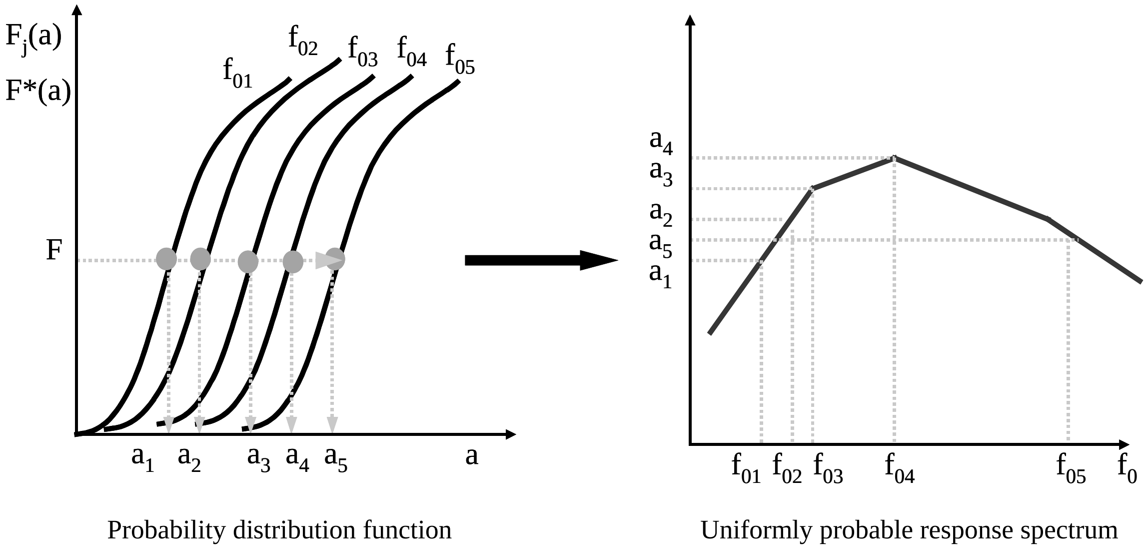
$$\alpha = \left(\frac{\frac{1}{\pi}\cdot\sqrt{\frac{\lambda_2}{\lambda_0}}\cdot\exp\left(\frac{-a^2}{2\cdot\lambda_0}\right)\cdot\left(1-\exp\left(-\sqrt{\frac{\pi}{2}}\cdot\frac{a}{\sqrt{\lambda_0}}\cdot\left(\sqrt{1-\frac{\lambda_1^2}{\lambda_2\cdot\lambda_0}}\right)^{1.2}\right)\right)}{\left(1-e^{\frac{-a^2}{2\cdot\lambda_0}}\right)} \right) \tag{2.b}$$

$$\lambda_i = \int_{w1}^{w2} \omega^i FDEP_{AA}(\omega) d\omega \tag{2.c}$$

where: F(a) probability distribution function not to exceed a response level a;
t* ground motion intensive phase duration;
λ_i the i-th order spectral moment;
$\omega_{1,2}$ limiting values of the interest frequency band.

Then, one varies the SS frequency, f_{0j}, and for each frequency value, one obtains the $PSDF_{AA}$(w), and its associated $F_j(a)$, Figure 1, left side.

Now, a level F of the $F_j(a)$ probability curves is considered and one takes the a_j values indicated on the same Figure 1, which represent for each frequency, the maximum response level with the assigned probability values F. This means that the a_j values represent, the SS response spectrum ordinates which have the probability F, not to be exceed by similar ordinate produced by an accelerogram with the same $PSDF_0$. And so, one reaches to the uniformly probable coupled response spectrum (UPCRS) for the SS shown in Figure 1, right side [8].



Probability distribution function

Uniformly probable response spectrum

Fig 1: Computational procedure schematic view. Uniformly probable response spectrum.

APPLICATIONS AND RESULTS

To illustrate the methodology one uses as primary structure a thermo-plant reactor building in which the superstructure is modelled by straight bar elements organized following three branches, representing the inner and outer concrete structures and the steel container, Figure 2.

The structure stiffness and mass are lumped distributed assuming an axial symmetric model. The foundation is rigid base modelled by 3D and 1D finite elements, Figure 3. Table 1 shows the primary structure natural frequencies. The 174 node is chosen to receive the single oscillator representative of the secondary system, Figure 2, and a 0.02 mass ratio is used.

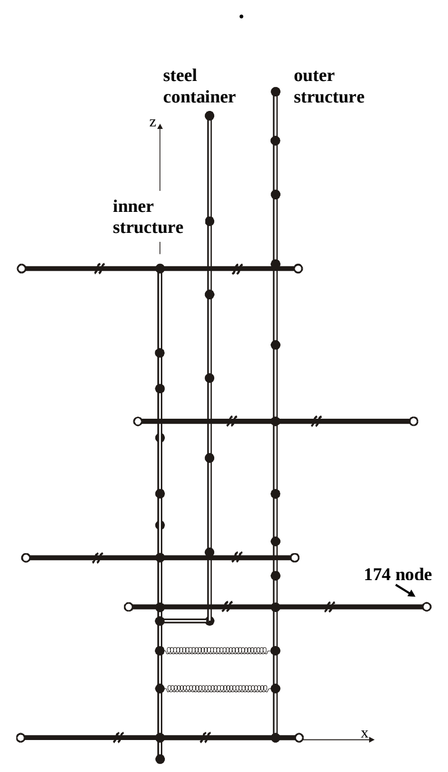


Fig 2: Model of superstructure

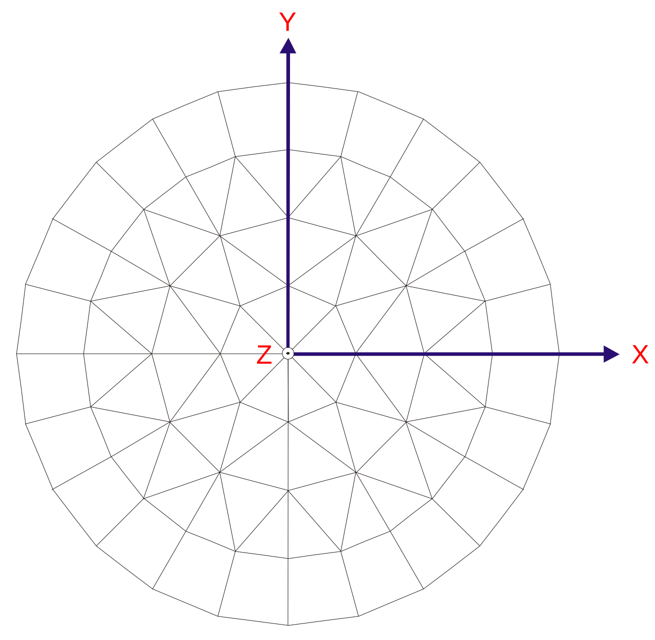


Fig 3: Rigid base model

Table 1: SP natural frequency

Mode	1	2	3	4	5	6	7	8	9	10	11	12	13
f (Hz)	*5.46*	*6.36*	*7.41*	*11.77*	*13.01*	*15.42*	*15.45*	*20.62*	*23.27*	*25.47*	*25.91*	*27.9*	*29.8*
Mode	14	15	16	17	18	19	20	21	22	23	24	25	26
f (Hz)	*32.0*	*32.9*	*38.9*	*39.1*	*41.5*	*43.1*	*44.6*	*45.6*	*47.6*	*48.5*	*50.0*	*54.7*	*57.1*

The excitation to the structure is taken to be the ground acceleration time-history showed in Figure 4.a (THA) which has been generated to accurately approach the NRC-RG 1.60 Design Response Spectrum [9] in Figure 4.b, with the maximum ground acceleration normalized to 1.0g. No total power control was made in this generation.

Figure 5 exhibits the 174 node coupled response spectrum together with the commonly used (uncoupled) design response spectrum; one may observe the differences between the two curves which indicate the convenience to use coupled response spectra, more in the interest of analysis consistency than in the way of economical profits.

Now, seeking for a probability based coupled design response spectrum one may use the just described methodology to obtain an UPCRS.

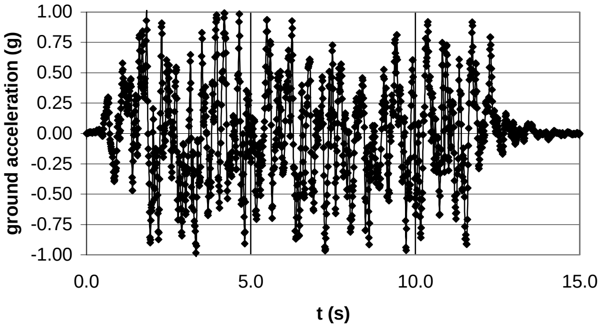


Fig 4.a: Acceleration time history, THA

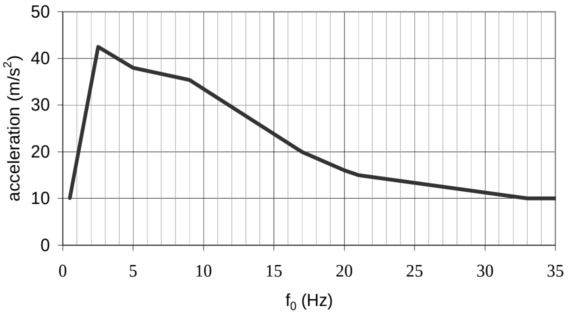


Fig 4.b: Design Response Spectrum

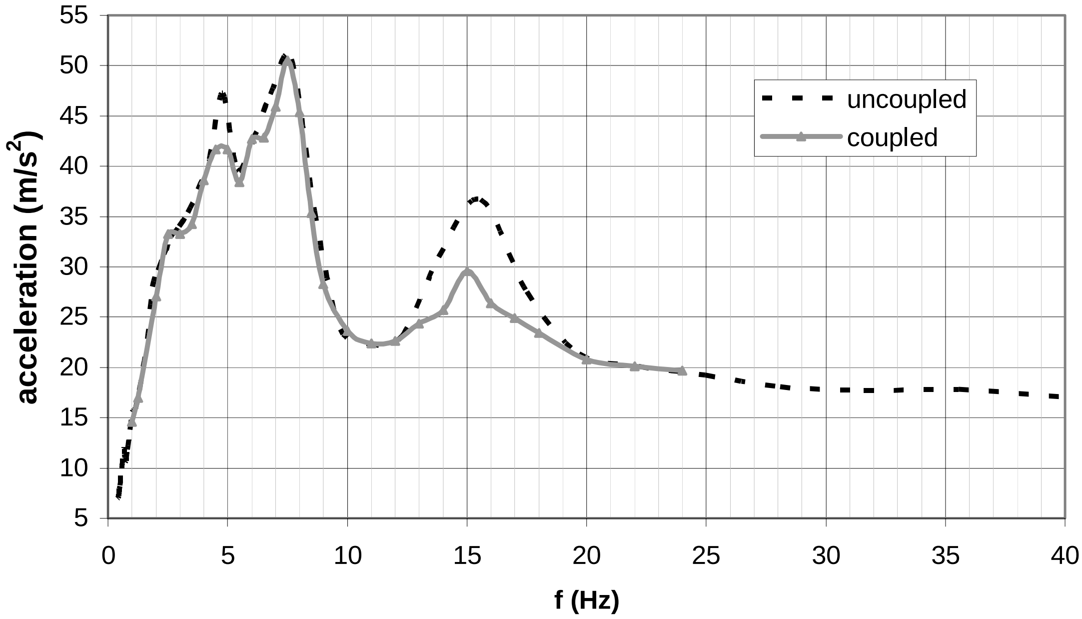


Fig 5: Node 174 response spectra – coupled and uncoupled - $\zeta = 0.05$

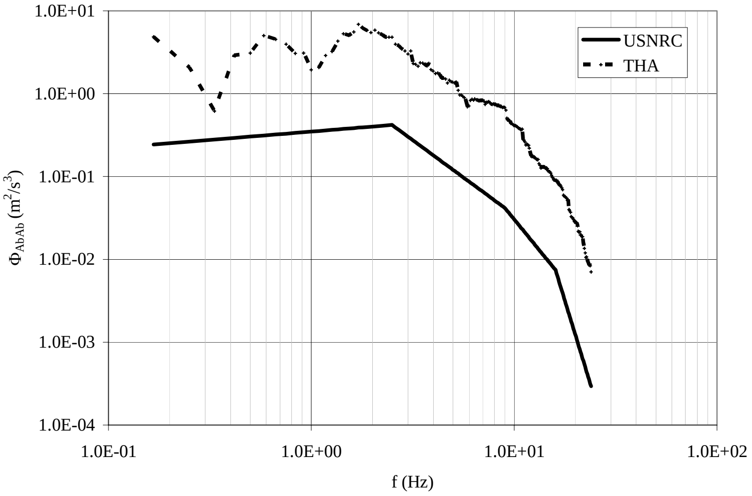


Fig 6: Ground acceleration power spectral density functions

Two ground acceleration $PSDF_0$ are considered as shown in Figure 6: (a) the USNRC $PSDF_0$ target [10] and (b) the power spectral density function of the ground acceleration time history, $PSDF_0$-THA.

The two curves present a large difference in the total power since no power control was made in the generation of THA time-history. In spite of this, the USNRC RG1,60 design response spectrum is very closely reproduced by the THA time-history. The necessity to have a tight control on the excitation total power and on its distribution over the main frequency region of the spectrum is not a new concern in seismic analysis.

The new concern is in Figure 7. One takes the uncoupled response spectrum ordinates in Figure 5 and computes, with the proposed methodology, the probabilities F_j (a_j) of these ordinates not to be exceeded when the primary structure is excited at its base by any ground motion belonging to the family defined by the $PSDF_0$-THA. It is found in Figure 7 that these F_j (a_j) probabilities are relatively low-valued but vary significantly, from 0 to 0.55.

If one does the same using USNRC $PSDF_0$ target the F_j (a_j) probabilities are all equal 1, over the complete frequency axis, and this should be expected since there is a large difference of power between the two $PSDF_0$.

This observation is quite uncomfortable to the analyst, to realize that the secondary system design response spectrum is quite variable in probabilistic terms.

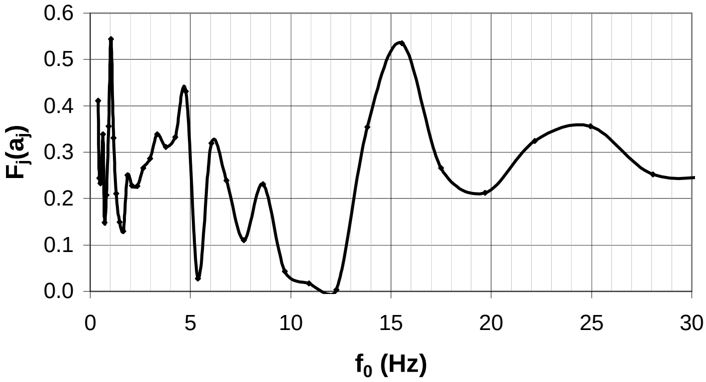


Fig 7: Probabilities $F_j(a_j)$, of the node 174, uncoupled response spectrum ordinates not to be exceeded by THA family

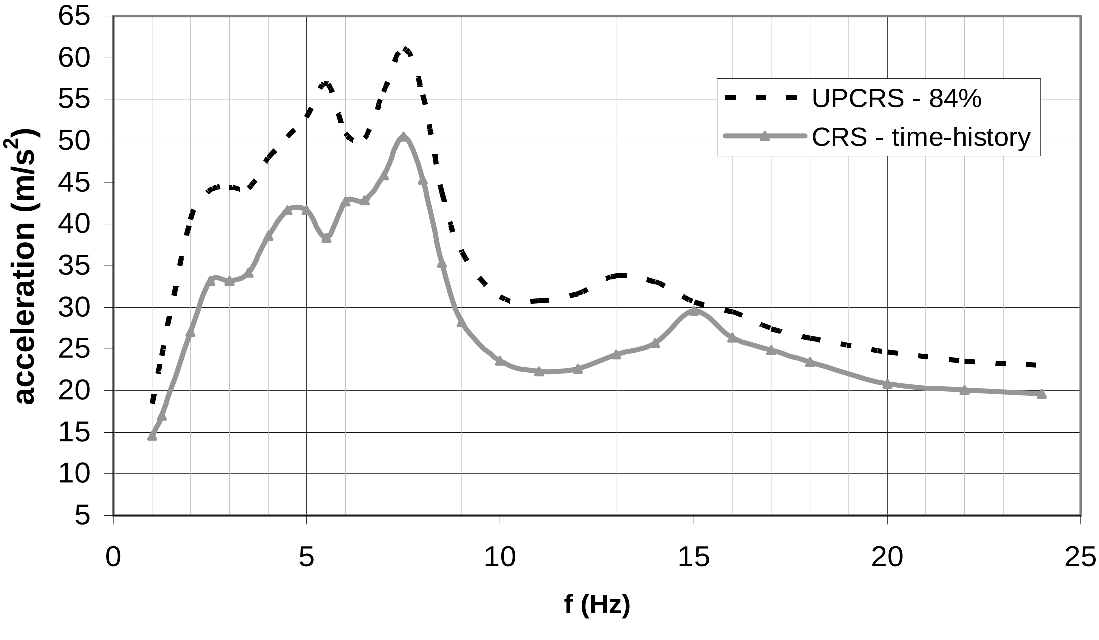


Fig 8: Uniformly probable coupled response spectrum for secondary systems – UPCRS - ζ=0.05 – THA excitation

Figure 8 shows the new proposal of an UPCRS, dashed curve, settled to a 84% probability level which can be comfortably used in design. The other curve is the coupled response spectrum (CRS) obtained from the THA time-history.

Naturally, the 84% uniformly probable coupled response spectrum envelops the coupled response spectrum obtained for the THA time-history alone because the form represents, in probabilistic terms, the second system response to all the infinite number of time histories which may have the same $PSDF_0$-THA.

CONCLUSIONS

One methodology is presented to obtain uniformly probable coupled response spectra for secondary systems starting from a site seismicity definition based on a ground acceleration power spectral density function.

The methodology is quite simple and specially recommended to the case of secondary systems which are large in number and carry a formidable diversity. Furthermore, as it uses only transfer function in the calculation a coupled analysis is easily performed and the parameter frequency dependence is also directly incorporated including soil structure interaction effects.

The definition of a power spectral density function to represent the site seismicity is a major task which can be achieved as the number of recorded earthquakes in the site region increases.

In the mean time, approximated function shapes with a reasonable conservatism degree may be a good attitudes.

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