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On the generation of inelastic secondary system seismic response spectra

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1 ABSTRACT

A procedure is presented to generate secondary seismic response spectra, which includes a probabilistic approach and considers coupling effects between primary and inelastic secondary systems. The analysis is performed in the frequency domain, with *SASSI2000* system. A set of auxiliary programs are developed to consider three-dimensional models and their responses to a generic base excitation, acting in 3 orthogonal directions.

The ground excitation is transferred to a secondary system SDOF model conveniently attached to the primary system. Then, a uniformly probable coupled response spectrum is obtained using a first passage analysis.

A global ductility factor, related to specified yielding level allows one to obtain transposition factors from elastic to inelastic response spectra. An example of a pipeline system used in nuclear power plant illustrates the proposed methodology; the obtained results permit to identify the differences between inelastic and elastic response spectra, specially, in some specific frequency range.

2 INTRODUCTION

In the electric nuclear power industry all safety related systems are designed to resist and to keep the operability during and after a postulated earthquake. The diversity and the large number of the secondary systems in a NPP lead to the response spectra methodology for the seismic analysis.

A lot of works have been presented related to this procedure, but still nowadays many questions are not completely answered, and the engineer assumptions lead to different amount of conservatism in the analyses results, as mentioned by Vasilyev (2007). Generally, artificial ground motions are applied at the primary system (PS) base, the structural responses are obtained in time domain using modal analysis or direct integration solutions, and floor response spectra are developed for the design of the secondary systems (SS). When using modal analysis, each modal damping coefficient is calculated considering an average of strain energy, compatible to the modal vector displacements; but it is not possible to represent the soil damping in a realistic way. The direct integration allows taking into account the local damping and the local nonlinear behaviour, then, the soil high damping characteristics can be considered. But the structural element loss of energy is represented by the Rayleigh damping, that is defined to the whole structure for the complete frequency range, leading to still more conservative results.

The present paper proposes a procedure to achieve more realistic in-structure floor response spectra by considering the seismic excitation in a probabilistic way, the PS and SS coupling influence and the dynamic and ductility characteristics of the piping secondary systems. As the proposed procedure is performed in frequency domain, the soil-structure interaction and damping behaviour can be well represented, considering its variation with frequency.

In general the SS seismic design is based on floor response spectra, which are produced by the seismic excitation acting on their support locations. The assumption of linear analysis is inherent to the response spectra methodology, although, it can be very useful to evaluate the plastic reserve due to SS ductility.

Sampaio (2003) and Gomes (2005) present a methodology to obtain transposition factors from elastic to inelastic response spectra. These factors are presented as a frequency function and they are used to evaluate the ductility influence on similar piping secondary systems.

3 FLOOR RESPONSE SPECTRA GENERATION

The calculation of the structural response in frequency domain permits the use of the seismic input in a probabilistic way. For this, the seismic excitation is represented by the one-sided power spectral density function PSDF$_o$=$\Phi_b(\omega)$, instead of the control point acceleration time history. In sequence, the power spectral density function of the primary structural joint response, PSDF$_s$=$\Phi_{u_s}(\omega)$, is obtained through well known transmissibility function.

Using the SASSI2000 the global seismic movement is represented by the equations (1) and (2):

$$\begin{bmatrix} C_{ss} & C_{si} \\ C_{is} & C_{ii} - C_{ff} + X_{ff} \end{bmatrix} \cdot \begin{Bmatrix} U_s \\ U_f \end{Bmatrix} = \begin{Bmatrix} 0 \\ X_{ff} \cdot U'_f \end{Bmatrix} \qquad (1)$$

$$C(\omega) = K - \omega^2 .M \qquad (2)$$

where K and M are the complex stiffness and mass matrices of the complete system; U is the complex nodal displacement vector; U'_f is the free-field complex displacement vector and X_{ff} is the impedance matrix of the system. All the interaction nodes, *i*, are shared by the structure and soil foundation. First the system solution is obtained for each frequency of analysis ω in terms of transfer functions $H(\omega)$. Once the transfer functions are obtained, the structural nodal responses $U(\omega)$ can be correlated to the input excitation acting at the control point, using its Fourier Coefficients $F(\omega)$, by the equation (3):

$$U(\omega) = H(\omega) \cdot F(\omega) \qquad (3)$$

If the seismic movement is represented by the base acceleration one-sided power spectra density function $\Phi_b(\omega)$, then the PSD of the structural nodal response is given by equation (4).

$$\Phi_{u_s}(\omega) = (H(\omega))^2 . \Phi_{u_b}(\omega) \qquad (4)$$

In general, seismic input motion considers 3 orthogonal components, so the *SASSI2000* solution for each component are superimposed, combining all nine responses, as presented in equations (5), (6) and (7):

$$\ddot{U}_{sX}(\omega) = H_{XX}(\omega) F_{bX}(\omega) + H_{YX}(\omega) F_{bY}(\omega) + H_{ZX}(\omega) F_{bZ}(\omega) \qquad (5)$$

$$\ddot{U}_{sY}(\omega) = H_{XY}(\omega) F_{bX}(\omega) + H_{YY}(\omega) F_{bY}(\omega) + H_{ZY}(\omega) F_{bZ}(\omega) \qquad (6)$$

$$\ddot{U}_{sZ}(\omega) = H_{XZ}(\omega) F_{bX}(\omega) + H_{YZ}(\omega) F_{bY}(\omega) + H_{ZZ}(\omega) F_{bZ}(\omega) \qquad (7)$$

Each of the seismic input excitation direction is associated to the same PSDF$_0$, then the transference of seismic movement energy at each global direction can be obtained using an equivalent transfer function $\overline{H}(\omega)$, equations (8), (9) and (10).

$$\overline{H}_X(\omega) = \sqrt{(H_{XX}(\omega))^2 + (H_{YX}(\omega))^2 + (H_{ZX}(\omega))^2} \qquad (8)$$

$$\overline{H}_Y(\omega) = \sqrt{(H_{XY}(\omega))^2 + (H_{YY}(\omega))^2 + (H_{ZY}(\omega))^2} \qquad (9)$$

$$\overline{H}_Z(\omega) = \sqrt{(H_{XZ}(\omega))^2 + (H_{YZ}(\omega))^2 + (H_{ZZ}(\omega))^2} \qquad (10)$$

With these functions and plus the base acceleration power spectrum density function $\Phi_b(\omega)$, the power spectral density functions for the structural point response components, $\Phi_{u_{sj}}(\omega)$, are obtained.

Considering the seismic movement as a Gaussian stationary random process, the proposed method by Almeida (2003), is used for generation of uniformly probable response spectra (UPRS), which is defined by the maximum response of a single degree of freedom (SDOF) system with equal not to be exceeded probability, along the usual frequency range of analysis.

Specifyed the not to be exceeded probability, the first passage problem formulation proposed by Vanmarke (1975) is used to obtain the response peak values distribution. Then, the probability of exceedance of a specific barrier value, *a*, during the excitation period, *t** is estimated:

$$L\ (t^*) = 1 - \left[\left(1-e^{\left(\frac{-a^2}{2.\lambda_0}\right)}\right)\exp\left(-\frac{\frac{1}{\pi}.\sqrt{\frac{\lambda_2}{\lambda_0}}.e^{\left(\frac{-a^2}{2.\lambda_0}\right)}.\left[1-e^{-\left(\sqrt{\frac{\pi}{2}}.\frac{a}{\sqrt{\lambda_0}}\left(\sqrt{1-\frac{\lambda_1^2}{\lambda_2.\lambda_0}}\right)^{1.2}\right)}\right]}{1-e^{\left(\frac{-a^2}{2.\lambda_0}\right)}}t^*\right)\right] \tag{11}$$

where $\lambda_i = \int_{\omega 1}^{\omega 2} \omega^i . \Phi_{u_s}(\omega) \mathrm{d}\omega$ i = 1,2,3 (12)

3.1 Coupling effects between primary and secondary systems

In order to include coupling effects on the floor response spectra generation, a SDOF with a variable natural frequency ω_{oi}, is used to represent the secondary system with mass m_i, connected to the primary system at their support points. Then, for each ω_{oi} the PSDF$_s$ is computed, representing the coupled SS response at this frequency. So, the probabilistic methodology described above produces a uniform probable coupled response spectrum UPCRS.

Relative displacements between the SS supports can be considered by connecting the SDOF to the different points of the PS model which better represent the support locations. For this, the coupling stiffness is subdivided proportionally to the local stiffness of the PS at the support point locations.

The *SASSI2000* module *MOTOR* is used to compute the local stiffness at the PS, at each point where the SS is supported. The same frequencies ω_{oi} are used and displacement transfer functions, DTF, are obtained for unitary load acting on these points. The inverse of DTF obtained for direction j at support point n is used to compute the local stiffness of the PS at this point $ksp_{n,j}(\omega_{0i})$, according to equation (13):

$$ksp_{n,j}(\omega_{0i}) = \frac{1}{\left|DTF_{n,j}(\omega_{0i})\right|} \tag{13}$$

Then, the local stiffness corresponding to each support point *n*, acting at the direction *j*, for each frequency of analysis ω_{oi} is given by the equation (14):

$$k_{n,j}(\omega_{oi}) = \omega_{0i}^2 . m_i . \frac{ksp_{nj}(\omega_{0i})}{\sum_1^n ksp_{nj}(\omega_{0i})} \tag{14}$$

With a conveniently choice of the frequency values ω_{oi}, representing all peaks and valleys of the equivalent transfer functions, one can interpolate the maximum values of the response for the generation of the UPCRS, for instance.

3.2 Transposition factors and inelastic floor response spectra

For some piping secondary systems it may be useful to consider their own characteristics that can influence their dynamical responses, such as pipe and support material inelasticity, operational stress level, temperature and internal pressure.

Sampaio (2003), for simplified SS, proposes a methodology to consider the influence in the response spectra of pipe elements inelasticity and supports. The system overall ductility factor is used to relate, qualitatively and quantitatively, the response spectra under elastic and inelastic behaviour.

Gomes (2005) enhanced the method on the influence of element static loads due to internal pressure and temperature variation on the elastic and inelastic response spectra relationships. Approximated response spectra for inelastic coupled response spectra of simplified SS are proposed. By the use of the transposition factors proposed by Gomes, the plastic reserve of similar SS under inelastic behaviour can be evaluated.

The transposition factors are tabulated for different yielding factors, *C*, stiffness factors, *N*, material damping coefficients, ξ , and frequency values. The yielding factor is related to the SS maximum stress level during the excitation, by the expressions 15.

The stiffness factors are related to the inelastic properties of the supports (*N1*) and pipe (*N2*) materials, using the relations presented in Figure 1.

$$C = \frac{\sigma_y}{\sigma_0} \leq 1 \qquad N1 = \frac{K2}{Ka} \qquad N2 = \frac{E2}{E1} \qquad (15)$$

3.3 Developed programs

In this work, the *ExeSASSI* program is created to manage *SASSI2000* several modules. The post-processor new programs *SomaMOT*, *GFiBase* and *ExConf* are also managed by the *ExeSASSI* program. All these modules are used in sequence and the maximum acceleration response of the SDOF, representing the SS, is obtained for each frequency of analysis. The SS maximum responses obtained for each one of these frequencies maintain the same not to be exceeded probability.

The computer program *SomaMOT.exe* is written to obtain the equivalent transfer functions $\overline{H}(\omega)$, from the results computed by *SASSI2000*. Two others programs, *GFiBase.exe* and *ExConf.exe*, are implemented in order to take the results from *SomaMOT* and to obtain power spectral density function and the uniformly probable response spectra (UPRS).

When the UPCRS is evaluated, a complete dynamic analysis is performed using the *SASSI2000*, for each frequency. The *ExeSASSI* manages all the analyses with *SASSI2000*, *SomaMot*, *GFiBase* and *ExConf*, for all frequencies of analyses,conveniently modifying the SS characteristics.

4 EXAMPLE DESCRIPTION

4.1 Mathematical modelling

The methodology is illustrated with the same Almeida (2003) sample model. A lumped mass beam model represents a reactor building similar to the Brazilian Angra 3 PWR. The circular plate foundation (weight 147 MN) is directly founded on rock and is considered infinitely rigid, Fig. 2a. Three beam branches, Fig 2b, are used to represent the external structure (268 MN), the steel container (57 MN) and the inner structure

(816 MN), where the nuclear reactor and the 4 reactor coolant loops are located. The total PS weight is 1288 MN. Table 1 presents the natural frequencies of the model.

A piping secondary system (0.55 MN), supported partially on inner and on external structure, is modelled by a SDOF attached to both model branches, at nodes 155, 174 and 176. Uniformly probable response spectra are obtained using the TF directly from control point, located at the base foundation, to the coupled SS mass node. Then, the influences of coupled mass, as well as the support point different stiffness and relative movements, are automatically included in the responses.

The equivalent TF from the seismic control motion at the base of the model to the nodes 155, 174 and 176 are presented in Figures 3a to 3c. These nodes represent the SS support points and, as it can be seen in Figure 3, they are excited differently by the same earthquake. The correspondence between the TF peak value frequencies and the natural frequencies of the model are expressed in the figures. All frequencies of analyses used by SASSI2000 soil-structure interaction analysis are pointed on these figures.

4.2 Seismic excitation

The Seismic Design Response Spectrum considers a 0.1g ground horizontal peak acceleration. For the vertical direction 2/3 of this value is considered. Figures 4a and 4b present the DRS and the correspondent $PSDF_o$ respectively. The excitation is to be applied simultaneously on the three orthogonal directions but, due to axial symmetry of the model, only one horizontal excitation is used together with the vertical one.

4.3 Uniformly probable coupled response spectra - UPCRS

Table 2 presents the frequencies of analysis used for the generation of the coupled response spectra. For each of them, the natural frequency of the SDOF representing the SS is adjusted and a complete frequency domain soil-structure interaction analysis is performed. The maximum SS acceleration response with 84% of not to be exceeded probability is evaluated and the interpolation of these values furnishes the UPCRS.

The PSDF of the acceleration responses are presented in Figures 5a to 5c for the SS support points on nodes 155; 174 and 176.

Figure 6a presents the envelope of the UPRS calculated for SS support nodes 155, 174 and 176 for horizontal and vertical responses. These enveloped UPRS can be used for the design of the SS in an uncoupled SS design modal analysis. The generated uniformly probable response spectra are smoother than those usually obtained by artificial acceleration time histories.

Figure 6b shows the horizontal UPCRS for node 181, representing the coupled response for the specific SS, considered in this sample with a total weight 0.55MN. Then, the total mass ratio is of about 0.04%. The frequencies of analyses used for the development of the UPCRS are pointed. The use of the coupled response is more realistic, because besides the mass coupling effects, it includes also the multiple support influence. The UPCRS can be used for the design of the SS.

Figures 7 present a comparison between elastic and inelastic uniformly probable response spectra for a secondary system. Figure 7a shows the influence of inelastic behaviour when the SS is beyond yielding stress with C=0.60. Figure 7b considers yielding factor of C=0.20. In both cases the same SS is used, with stiffness factors N1=1 (linear supports) and N2=0.3 (non-linear pipe material). By the comparisons it can be concluded that a plastic reserve for frequencies above 7 Hz is expected, but for SS mode shapes with frequencies higher than this value, the SS can be overstressed in relation to the linear design.

5 TABLES AND FIGURES

Table 1 Natural frequencies of the primary system model

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*

Table 2 Frequencies of analysis for coupled response spectra [Hz] – 30 values

0.05	*1.02*	*2.00*	*2.78*	*3.56*	*4.35*	*5.13*	*5.37*	*5.86*	*6.35*
6.59	*6.84*	*7.18*	*7.47*	*7.81*	*8.15*	*8.50*	*8.94*	*9.38*	*9.86*
10.35	*11.82*	*12.79*	*13.77*	*14.75*	*15.72*	*17.68*	*19.63*	*21.58*	*24.02*

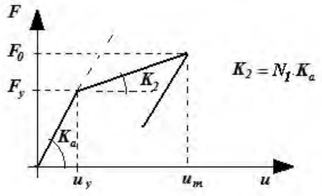

Figure 1 Nonlinearity relations

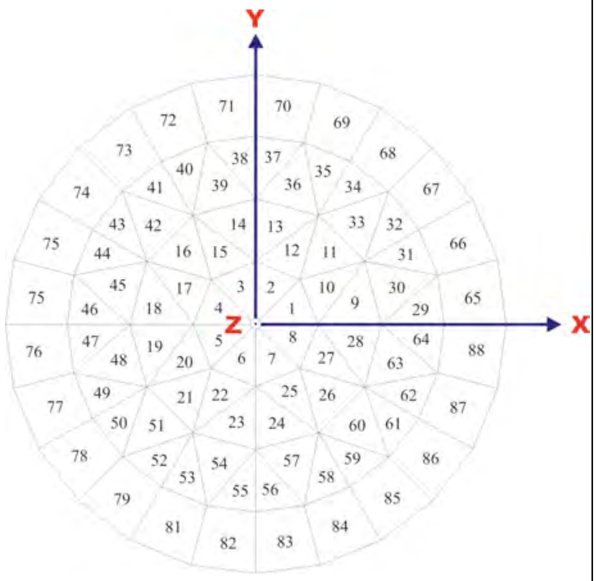

Figure 2a Circular plate foundation

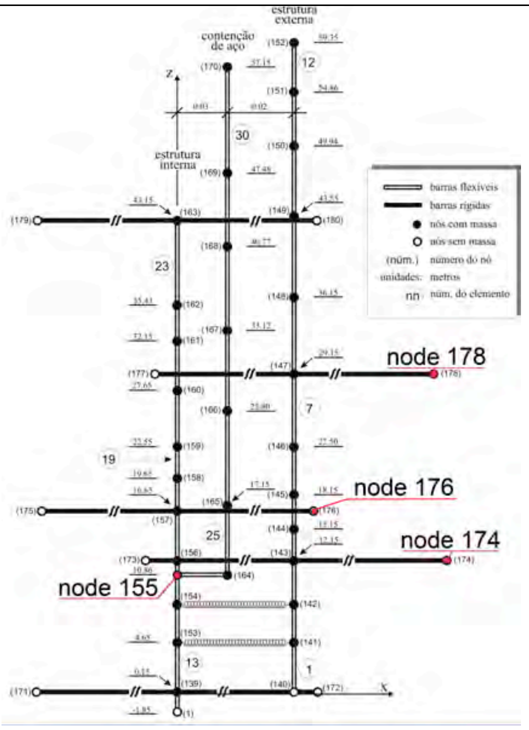

Figure 2b Beam model of the superstructure

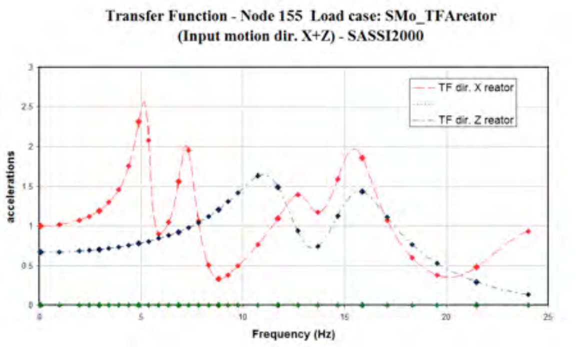

Figure 3a TF to node 155 - internal structure

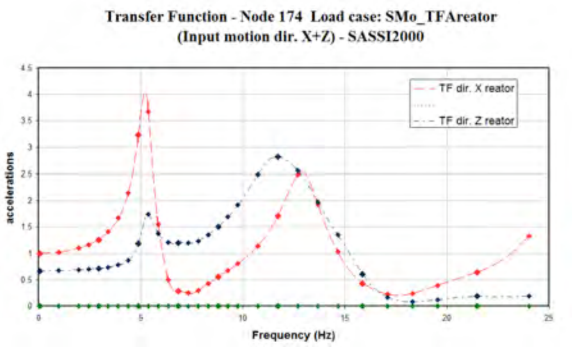

Figure 3b TF to node 174 - external structure

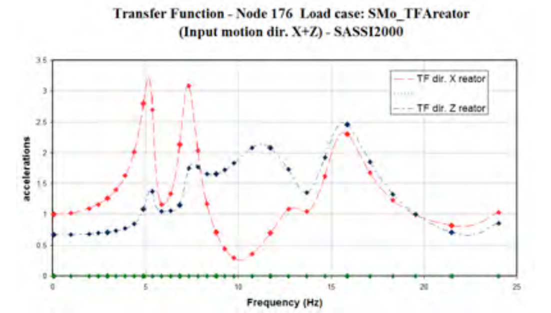

Figure 3c TF to node 176 - internal structure

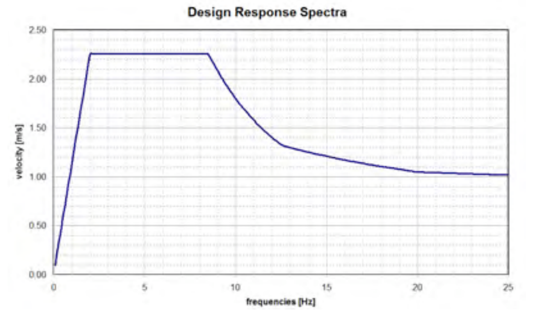

Figure 4a Horizontal Design Response Spectrum

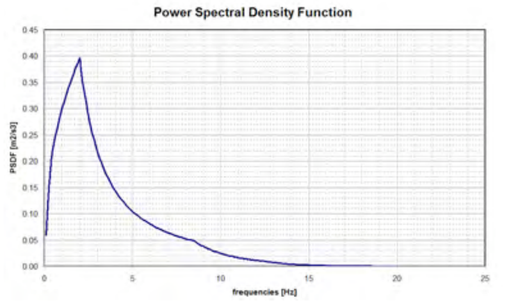

Figure 4b Design Power Spectral Density Function

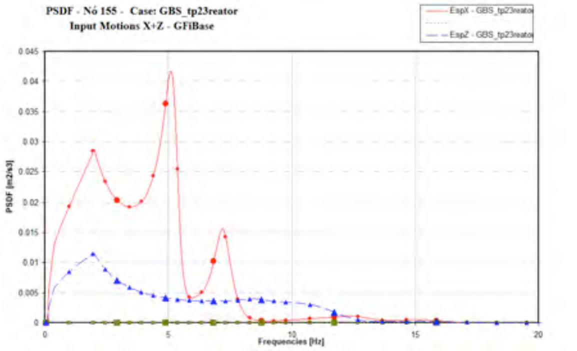

Figure 5a Node 155 PSDF – internal structure

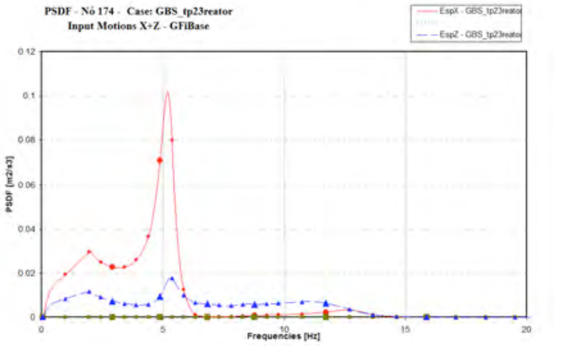

Figure 5b Node 174 PSDF – external structure

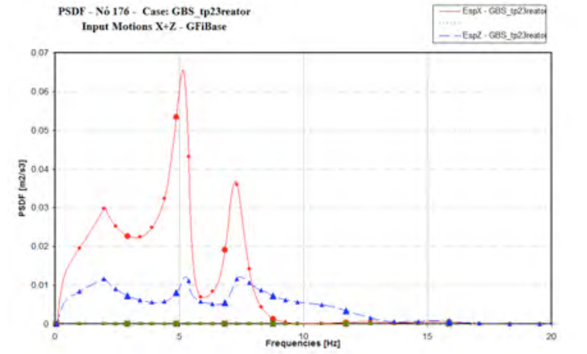

Figure 5c Node 176 PSDF– internal structure

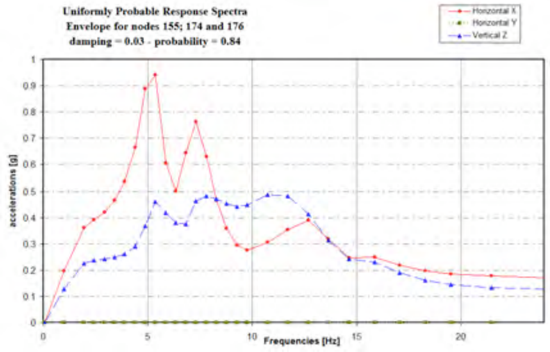

Figure 6a UPRS – uncoupled analysis envelope for nodes 155; 174 and 176

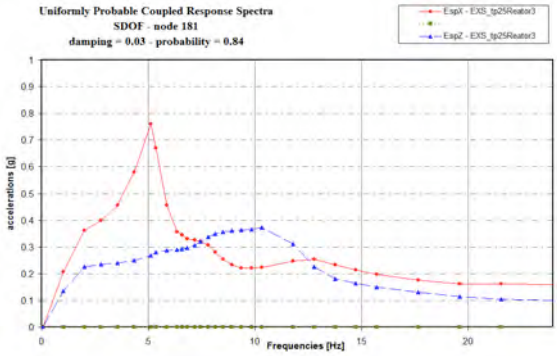

Figure 6b UPCRS – node 181 for coupled Secondary System

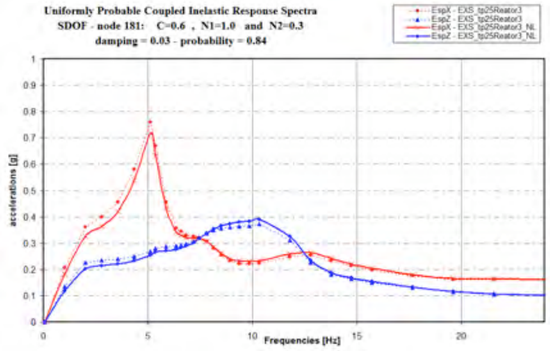

Figure 7a UPCRS and UPCIRS

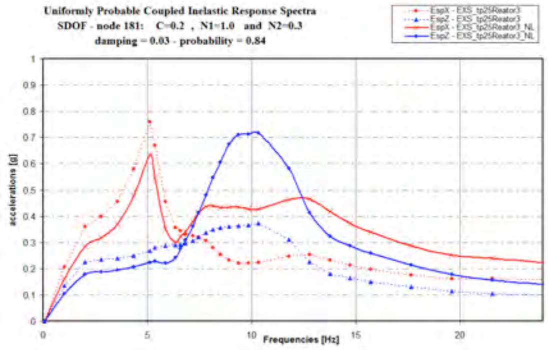

Figure 7b UPCRS and UPCIRS

6 CONCLUSION

An overview is taken on different ways and extensions to obtain a secondary system seismic response spectrum in a frequency domain scenary as the one which is open by SASSI. Special situations are considered as the interaction of the main and the secondary system properties, the effect due to a multiple supported secondary system situation, the consideration of a uniform probability response spectrum, and, in all cases, the evaluation of the secondary system ductile storage extension, that is, its complacency.

With the proposed methodology one can achieve the following advantageous:

- Better damping effects representation, considered directly in the soil-structure interaction formulation, because neither the use of modal damping nor the definition of the Rayleigh coefficients are necessary.

- The choice of the frequency for which the response spectrum is calculated is oriented by the transfer function peak values. It requires a lower number of calculations point than if all modal frequencies are used besides those 75 specified ones [US NRC- RG 1.122 – 1978].

- Superposition and combination of different responses can be obtained under probabilistic point of view.

- Probabilistic response spectra, obtained directly from PSDF, are much smoother than those obtained deterministically from time history samples, and the errors can be evaluated, leading to more analysis reliability.

- Possibility of easy evaluation of the ductil reserve of secondary systems under inelastic behaviour.

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